Non-Dyadic Collaboration In Human-Robot Interaction

Schneiders, Eike

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BY
EIKE SCHNEIDERS

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by Eike Schneiders

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PhD supervisor: Professor Mikael B. Skov,
Aalborg University, Denmark

Assistant PhD supervisors: Professor Jesper Kjeldskov,
Aalborg University, Denmark

Associate Professor Niels van Berkel,
Aalborg University, Denmark

PhD committee: Associate Professor John Stouby Persson (chairman)
Aalborg University, Denmark

Professor Torkil Clemmensen
Copenhagen Business School, Denmark

Professor Lynne Baillie
Heriot-Watt University, Scotland

PhD Series: Technical Faculty of IT and Design, Aalborg University

Department: Department of Computer Science

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ENGLISH SUMMARY

With the ever-increasing number of domains in which we encounter robots—be it in industry, airports, or the home—the opportunity to interact and collaborate with these grows. And while an abundance of Human-Robot Interaction (HRI) literature has investigated dyadic interaction, non-dyadic HRI research, i.e., more than one human and one robot, has just recently begun to receive increasing attention. In this dissertation, I investigate characteristics of *non-dyadic* Human-Robot Interaction and collaboration. Specifically, I investigate two research questions focusing on i) the identification of existing characteristics of non-dyadic Human-Robot Interaction research and ii) the influence robots have on non-dyadic collaborative efforts.

This dissertation's contribution is based on five research papers. Paper I presents an empirical investigation of existing research on non-dyadic HRI over the last 15 years. Paper II to IV present qualitative field studies in the domestic and industrial contexts. Lastly, Paper V presents a mixed-methods lab-based study investigating human group collaboration and identifies design considerations to improve non-dyadic human-robot collaboration. Based on these five papers, this dissertation presents two primary contributions.

Firstly, I identify characteristics of non-dyadic HRI through an investigation of 164 research papers. These characteristics include the ongoing paradigm shift from a dyadic focus towards a non-dyadic focus, three non-dyadic configurations within HRI (one-to-many, many-to-one, and many-to-many) and an imbalance emphasising research involving one human interacting with multiple digital artefacts (one-to-many), a classification framework for non-dyadic Human-Robot Interaction, as well as empirical evidence showing the focus of non-dyadic HRI research on simultaneous over sequential interaction.

Secondly, I present several ways in which robots influence collaboration during non-dyadic Human-Robot Interaction. I highlight how introducing robots in both the domestic and industrial contexts into non-dyadic settings can lead to a fragmentation of previously coherent tasks while only some of the sub-tasks are automated. Furthermore, I show how the robot's presence, as previously hypothesised—can lead to a spatial restructuring resulting in a positive change in interpersonal relationships amongst collaborators. Lastly, I argue for the robot's capacity to alter, remove, and create roles and responsibilities within the non-dyadic collaborative Human-Robot Interaction.

Future work includes the investigation of i) robots as pro-active collaborators, ii) increase of transparency during robot introduction to counter unintended negative side-effects, and iii) a reconsideration of what a collaborative robot and collaboration with robots means.

DANSK RESUMÉ

I takt med at vi møder robotter inden for et stigende antal af områder, såsom i industrien, lufthavne og i hjemmet, øges muligheden for at interagere og kollaborere med disse. Hovedparten af Human-Robot Interaction (HRI) forskning har undersøgt dyadiske interaktioner, mens non-dyadic HRI-forskning, mellem flere mennesker og robotter, kun for nyligt er begyndt at opleve et større fokus. I denne afhandling har jeg undersøgt hvad der karakteriserer *non-dyadic* HRI og kollaboration. Specifikt har jeg undersøgt to forskningsspørgsmål som fokuserer på i) identifikationen af eksisterende karakteristika i non-dyadic Human-Robot Interaction samt ii) robotters indflydelse på non-dyadic kollaborationer.

Bidraget i denne afhandling er baseret på fem forskningsartikler. Artikel I beskriver en empirisk undersøgelse af eksisterende forskning indenfor non-dyadic HRI over de sidste 15 år. Artikel II til IV præsenterer feltstudier i den domestiske samt industrielle kontekst. Endelig, præsenterer Artikel V et labstudie, som undersøger kollaboration i grupper, og identificerer design overvejelser til non-dyadic human-robot kollaboration. Baseret på disse fem artikler, fremfører denne afhandling to primære bidrag.

For det første, baseret på en undersøgelse af 164 forskningsartikler som omhandler non-dyadic Human-Robot Interaction, identificerer jeg karakteristika af non-dyadic HRI. Disse inkluderer et igangværende paradigme skift fra et dyadisk fokus til et non-dyadic fokus, tre non-dyadic konfigurationer indenfor HRI (en-til-mange, mange-til-en, og mange-til-mange) samt en ubalance som fremhæver forskning der involverer et menneske, som interagerer med flere digitale artefakter (en-til-mange), et klassifikations framework for non-dyadic Human-Robot Interaction, såvel som empirisk evidens som fremhæver et fokus i non-dyadic HRI på studier der undersøger simultan frem for sekventiel interaktion.

For det andet præsenterer jeg måder hvorpå robotter påvirker kollaborationen i non-dyadic Human-Robot Interaction. Jeg fremhæver, hvordan introduktionen af robotter i både den domestiske samt industrielle kontekst kan lede til fragmenteringen af førhen sammenhængende opgaver mens kun del-opgaver bliver automatiseret. Endvidere viser jeg, hvordan robotters tilstedeværelse kan lede til en omstrukturering af de rumlige forhold, og hvordan dette kan medføre en positiv udvikling Af relationerne blandt kollaboratørerne. Afslutningsvist fremhæver jeg robotters evne til at modificere, fjerne, eller tilføje nye roller samt ansvarsområder til interaktionerne i non-dyadic Human-Robot Interaction.

Fremtidigt arbejde inkluderer undersøgelsen af i) robotter som pro-aktive kollaboratører, ii) en forøgning af gennemsigtighed ved introduktionen af robotter med henblik på at forebygge negative sideeffekter, samt iii) en genovervejelse af hvad en kollaborativ robot er og hvad det vil sige at samarbejde med robotter.

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DISSERTATION DETAILS

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Ph.D. Student: Eike Schneiders

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The following five papers represent the primary contribution of this dissertation:

1. **Eike Schneiders**, EunJeong Cheon, Jesper Kjeldskov, Matthias Rehm, and Mikael B. Skov. 2022. Non-Dyadic Interaction: A Literature Review of 15 Years of Human-Robot Interaction Conference Publications. *ACM Transactions of Human-Robot Interaction (THRI).* 11, 2, Article 13 (June 2022), 32 pages. https://doi.org/10.1145/3488242

2. **Eike Schneiders**, Anne Marie Kanstrup, Jesper Kjeldskov, and Mikael B. Skov. 2021. Domestic Robots and the Dream of Automation: Understanding Human Interaction and Intervention. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21).* Association for Computing Machinery, New York, NY, USA, Article 241, 1–13. https://doi.org/10.1145/3411764.3445629

3. EunJeong Cheon, **Eike Schneiders**, and Mikael B. Skov. 2022. Working with Bounded Collaboration: A Qualitative Study on how Collaboration is Co-constructed around Collaborative Robots in Industry. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

4. EunJeong Cheon, **Eike Schneiders**, Kristina Diekjobst and Mikael B. Skov. 2022. Robots as a Place for Socializing: Influences of Collaborative Robots on Social Dynamics In- and Outside the Production Cell. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

5. **Eike Schneiders**, Stanley Celestin, Christopher Fourie, Guy Hoffman, Julie Shah, and Malte Jung. 2022. Understanding Entrainment in Human Groups: Identifying Cobot Design Considerations based on Human Collaboration.

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1 INTRODUCTION

Over the last few decades, the expansion of robots has leapt forward in a multitude of application domains, resulting in increased encounters with robots in everyday life. Technological advancement, has led us to more often share our surroundings with robots. This can be seen in a multitude of contexts, including private settings (e.g., the home), commercial spaces (e.g., airports or assembly lines), as well as public spaces (e.g., recreational areas or parks). The key motivational aspect behind the advancement of robots into these and other spaces is often considered to be the robots' utilitarian qualities, such as their ability to perform mundane or repetitive tasks - thereby helping us achieve a specific goal. Examples include getting from point A to B, assisting in the assembly of a given product, as well as maintaining our houses and gardens. As a consequence of this expansion of robot tasks, humans will increasingly encounter, interact, and collaborate with robots. Whilst a large amount of prior work within Human-Robot Interaction (HRI) research has focused on the investigation of Human-Robot Interaction in controlled environments (e.g., controlled lab experiments or video vignettes), real-world interaction with robots is rarely this organised. Furthermore, the investigation of Human-Robot Interaction within a controlled environment makes it possible to guarantee that the interaction remains dyadic (i.e., *one* human interacting with *one* robot). In reality, this is seldom the case in the wild, as even systems intended for dyadic interaction might be approached by groups of people or depend on a multitude of other devices. Therefore, I argue, it is critical to investigate how robotic technology can be understood, optimised, and designed to interact and collaborate in scenarios involving more than one human user, robot, and other devices. The growing diversification of contexts in which robots can be encountered brings with it the need to better understand what characterises non-dyadic interaction and collaboration with and around this technology and how robots shape human interaction and collaboration within groups.

In this dissertation, I investigate the interaction and collaboration between humans and robots during non-dyadic Human-Robot Interaction.

Following the introduction, this dissertation will present background and related work (Chapter 2), an overview of the individual contributions of each paper (Chapter 3), a discussion of common topics that were identified from these (Chapter 4), as well as this dissertations' conclusion (Chapter 5) answering the two investigated research questions. The five papers included in this dissertation can be found in the Appendix.

1.1 What is a Robot?

Before delving into the details of what a robot is, I want to address the question why we should study interaction with robots in the first place. Since the commercialisation of the first Roomba cleaning robot in 2002, the presence of robots in the home has been ever-increasing, highlighted by the fact that an estimated 12% of all US households had at least one robot in their home in 2019 [28, 29]. This tendency has increased to other spaces such as airports (Figure 1.1a), public areas (Figure 1.1e), or restaurants (Figure 1.1f). With the distribution in real-world settings, it becomes increasingly important to understand how we interact with robots as well as how their presence affects collaboration with and around them.

To further exemplify robots presence in the real world, I want to draw from observations from personal experience to provide concrete examples of robots that encounter situations where the need for group-based interaction might arises. Figure 1.1 shows six pictures of robots that I had the chance to see (apart from Figure 1.1e[1]) in the wild—both privately and as part of research—during the duration of my Ph.D. since 2019. While robots might still seem 'a thing of the future,' these real world observations of robots demonstrate the variety of robots and contexts that already exist. These six examples of robots operate in vastly different domains (i.e., airports, private gardens, manufacturing industry, public spaces, and restaurants), yet all six examples are in positions where they might encounter and interact with multiple human(s) and other devices, including robots.

If we accept the premise that interaction with robots can be encountered in an ever-increasing number of domains, a clear understanding of what a robot is is important. When starting to investigate Human-Robot Interaction, one becomes aware of the diversity and abundance of different definitions for the term 'robot' as well as specific types of robots. The variety and diversity of these definitions is a direct reflection of the multidisciplinary field of HRI. In this dissertation I draw inspiration from Anca Dragan's understanding [48] of what a robot is:

> *'A robot is a physically embodied artificially intelligent agent that can take actions that have effects on the physical world.'*

This understanding has its onset in the presence, and need, for a *physical embodiment*, thereby removing such things as 'software robots' (i.e., algorithms) from the understanding of the term robot. Furthermore, the robot requires some sort of artificial intelligence (AI). While the term AI has become wildly popular, there is no easy answer to when something unambiguously classifies as artificial intelligence. The degree to which seemingly intelligent decisions need to happen is up for interpretation. Lastly, this view of what a robot is emphasises the robot's ability to 'take actions', or manipulate, the real world. This can be in a physical sense,

[1]Thanks to my friend and colleague Alisa Ananjeva for allowing me to use this photo.

(a) Customer-service robot

(b) Gardening Robot

(c) Cobot, assembly

(d) Cobot, welding

(e) Food delivery robots

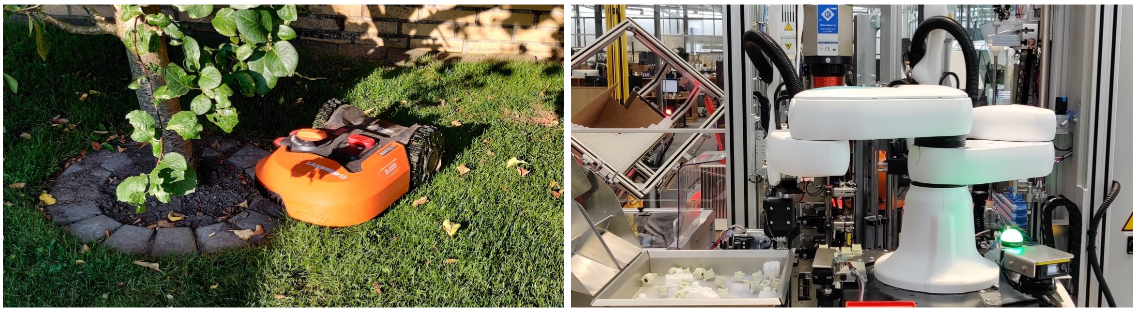
(f) Restaurant robots

Figure 1.1: Examples of six different types of robots observed in real world scenarios throughout the course of my Ph.D. (a) Customer-service and way finding robot at Incheon International Airport (2019). (b) Lawn-mowing robot observed during my second study (2020). (c) Industrial Collaborative Robot (Cobot) studied during field observations (2021) for third and fourth study. (d) Industrial Collaborative Robot (Cobot) used for welding (2021). (e) Food delivery robot on the Southern Methodist University campus, Dallas (2022). (f) Food delivery robots within a sushi restaurant in Southern Denmark (2022).

e.g., by picking up items or by mowing the lawn, to a more abstract world manipulation, e.g., making people smile or providing information. This also means that the context and perceived usefulness of the robot are not deciding criteria for a device to be considered a robot.

A common lens when characterising what a robot is, is the 'Sense-Plan-Act' paradigm [23]. This paradigm relies on three distinct criteria for a device to be considered a robot. These are the device's ability to perceive ('sense') its environment and use this information to compute ('plan') a course of action, followed by the execution ('acting') of the computed plan. The extent to which the robot needs to sense, plan, and act is quite flexible and can range from simple to complex implementations. An example from the simpler side of the scope could be a lawn mowing robot (see Figure 1.2a). While seemingly mowing the grass at random, countless cycles of 'sensing, planing, acting' lie behind its ability to perform this mundane task. A typical lawn mowing robot has several systems in place to inform it about potential collisions. The robot is able to sense the perimeter wire—a wire that is dug down around the perimeter—to detect when the edge of its mowing area has been reached. For obstacles within its mowing area—such as the tree in Figure 1.2a—the robot has a front bumper with connected accelerometers. On impact, these will provide information about a sudden deceleration, thereby indicating a collision. Provided with this information, the lawn mower starts computing (or planning) the appropriate course of action. Following a decision the appropriate action is taken, e.g., a rotation by a certain number of degrees and proceeding with the mowing process.

A different type of robot using the sense, plan, act paradigm can be found in industrial collaborative robots. On a high abstraction level, these robots do exactly the same as the lawn mower—sense, plan, act. However, when delving further into detail a lot of additional complexity might arise. The collaborative robot shown in Figure 1.2b uses visual information (sensing) collected through an over-head mounted camera (out of frame) to detect the orientation of objects in the metal box placed in front of it. Based on the processed data, it plans which object to pick up or to shake the box in order to rotate the objects (act). This process is repeated until at least one of the said objects is in the correct orientation for the robot to pick up the object.



(a) Lawn mowing robot **(b)** Industrial robot

Figure 1.2: Two examples of robots using the sense-plan-act paradigm. Left: a lawn mowing robot which detects collisions through an deaceleration measured using an accelerometer. Right: an industrial robot using visual information to detect the rotation of objects to pick up, based on the rotation the end-effector is adjusted to grasp the object.

1.2 Interacting with Robots

With the increasing presence of robots, a clear understanding of how we interact and collaborate with this new technology becomes increasingly relevant. To this end, the relatively young field of Human-Robot Interaction has made significant advances in understanding [72, 101, 105], designing [54, 59, 81] and influencing [87, 119] how we interact with robots. HRI research is often centred around a distinction based on the number of interaction partners, or the ratio between the two sides (i.e., humans and robots) (e.g., [104, 105, 136]). This distinction leads to two overall interaction scenarios, namely i) the dyadic interaction, or one-to-one, as well as ii) the non-dyadic interaction, i.e., multiple humans interacting with multiple robots. Most work within HRI research has focused on the investigation of HRI in a dyadic context [101]. While dyadic HRI is an important area of research, it comes with some limitations in terms of real-world applicability.

When interacting with robots in the real world, the interaction can quickly shift from dyadic to non-dyadic, e.g., additional people join the interaction. Examples of robots which might need to interact with both individuals and groups are way-finding robots in public environments such as airports (e.g., [64]), the Spot robot in Singapore enforcing social distancing during the Covid-19 pandemic [73], or domestic robots which foster new social interactions and collaborations not just with the robot(s) themselves, but also amongst the users (e.g., [59, 102]). The rapid growth of robot deployment [12, 75] emphasises the importance to understand how robots change interaction, collaboration, and team dynamics within mixed human-robot groups of various constellations.

But what characterises non-dyadic interaction with robots? The interaction with robots can take numerous shapes and forms ranging from physical co-located interaction [67, 69] to remote interaction [11, 113], span various input modalities (e.g., touch [108], speech [40], or controller based [128]), and different relations relation between human(s) and robot(s) (i.e., is the robot a tool [81], a collaborator or a competitor [76]). Furthermore, when investigating interaction with robots in mixed human-robot groups an additional phenomenon arises which can not be observed in the dyadic context. Namely the change in human-human relationship and collaboration due to the robot's presence. As previous research has shown (e.g., [65, 85]) the interaction with the robot changes not only how people interact with the robot, but also how they collaborate with each other. For instance, how does the interaction between group members change when a guide robot guides a group through an airport instead of guiding one person? Is the robot supposed to wait when one group member stops, or is the robot's walking behaviour tied to a specific person within the group? Do group members wait for each other or do they follow the robot until it stops? Another case is the industrial context, here questions arise such as; What impact does the introduction of industrial robots (e.g., cobots) have on industrial workers' relationship to each other [98]? Do industrial workers think of the robot as a tool they use, like a hammer, or as a collaborator, like a coworker? Which changes to the work routines are necessary when introducing mobile robots into a warehouse? Even in the home, the introduction of robots might change household members' behaviour [36, 59]. Does the change from a manually pushed lawn mower to a lawn mowing robot impact how members of the household collaborate around the task of mowing the lawn? Does the introduction of robot vacuums change who has responsibility for cleaning? These are just some example questions and contexts highlighting the vast variety of domains and tasks in which robots have the potential to affect interaction and collaboration with them, as well as other amongst collaborators and interaction partners.

The increasing distribution of robots in different domains leads to an increase in the number of contexts in which interaction and collaboration happen in groups. Examples of this include the manufacturing context or warehousing solutions. These domains are increasingly augmented with robots, while many tasks are characterised by the need for group collaboration.

Furthermore, when interacting in non-dyadic configurations the interaction has the additional complexity of Human-Human Interaction and collaboration, as well as the potential device-to-device interaction. How does the introduction of an industrial robot into an industrial production context change the relation and collaboration between a group of human collaborators within the production cell? Does the presence of the robot impact the communication and relationship humans have with each other? Questions like these can only be investigated when considering non-dyadic Human-Robot Interaction, as these phenomena do not occur in the dyadic context.

1.3 Collaboration with and around Robots

The introduction of robots into new contexts, i.e., the home or the workplace, can impact human-human relationships within the group, leading to a potential change of the entire interaction. This phenomena has been referred to as the 'ripple effect' [60,65,115]. It describes the effect that an initial interaction can have on the following interactions with others. This 'ripple' can propagate through the entire group interaction and beyond, vastly changing the way in which people and robots interact, collaborate, and structure the interaction within the group. When introducing robots e.g., in the manufacturing context, the question arises - how should workers collaborate with the new technology? However, the potential impact of the robot expands further than the interaction with the robot itself, as this interaction can affect subsequent interactions between different actors. As argued, robots increasingly become part of society and the world we live in. How we interact and collaborate with and around these becomes increasingly relevant. The presence of robots in spaces in which a multitude of people and other devices are present furthermore increases the likelihood for these devices to encounter situations in which they have to interact and collaborate with more than one actor at the same time. Domains such as health- and eldercare [85, 95, 124], public spaces [6, 64], teaching [55, 97], or manufacturing [22, 98, 109] are all examples of contexts which already experience a strong growth in both research activity as well as robot presence within the domain.

A common understanding of the term 'collaboration', or collaborative joint action, describes collaboration as *´any kind of action performed [by two or more actors] with a shared goal and does not imply precise coordination of any kind'* [91]. Within these constraints, two sub-categories exist, namely 'uncoordinated' and 'coordinated'. While during the 'uncoordinated' collaboration the reaching of the goal is not the results of a structured effort, the coordinated collaboration requires coordination along e.g., temporal and spatial dimensions. An alternative understanding of the term has been presented by Grosz [44], who defines collaboration along a similar line of thought. Grosz uses terms such as *'jointly with other actors'* or *'fulfil a specific intent [or goal]'* to describe the term collaboration. Furthermore, Grosz characterises the presence of the shared intention as the primary difference distinguishing 'collaboration' from 'interaction'. Both presented understandings of collaboration are characterised by their emphasis on two specific elements, namely the presence of *multiple entities or actors* as well as the focus on a *specific goal or intent*. Firstly, for collaboration to occur, multiple actors have to be present, and while this traditionally excluded systems, the state of modern systems—and their degree of agency—allows for them to be considered as agents with their own agency. Secondly, the focus on a shared goal or intention, two terms used synonymous in this dissertation. The robot's intent, such as the completion of a given task, represents the desired outcome of the collaborative efforts between actors.

In this dissertation, I investigate non-dyadic Human-Robot Interaction and characteristics of collaboration between multiple human(s) and/or robot(s). This includes both the goal oriented collaboration between human(s) and robot(s), but further expands to the robots impact on interpersonal relationships amongst actors.

1.4 Research Questions

As the previous sections highlight, the investigation of various aspects of non-dyadic Human-Robot Interaction is a topic of increasing relevance. Throughout this dissertation, I present empirical insights on how robots, as part of non-dyadic Human-Robot Interaction, influence collaborative effort. This section will present the two research questions and briefly highlight their individual focus points.

With the increasing complexity of Human-Robot Interaction research focusing on the non-dyadic context, my first research question is a guiding effort to identify common tendencies and trends in non-dyadic HRI research.

RQ1: *What characterises non-dyadic Human-Robot Interaction research?*

As the focus on non-dyadic Human-Robot Interaction is a rather recent trend, an empirical understanding and synthesis of the focus within the research community is valuable. The investigation of this research question constitutes a theoretical contribution based on a retrospective investigation and classification of existing non-dyadic research within the interdisciplinary field of Human-Robot Interaction.

The second research question is related to *collaboration* during non-dyadic Human-Robot Interaction. It investigates the robots impact collaboration between human(s) and robot(s) during non-dyadic Human-Robot Interaction.

RQ2: *What influence do robots have on collaboration in non-dyadic Human-Robot Interaction?*

The investigation is based on two different context in which collaboration with robots occurs, namely the industrial and the domestic context. The study of the second research question constitutes an empirical contribution, utilising both field- and lab based studies.

1. INTRODUCTION

2 BACKGROUND

This chapter will present relevant background and related work in relation to various aspects of non-dyadic HRI. This includes different understandings of the term 'robot', thereby contextualising why the, in this dissertation used, robot understanding was selected and is applicable to this work. Secondly, I will present a multitude of taxonomies and classifications used to acquire a broader understanding of the field at large. Thirdly, I will give a brief overview of dyadic research, thereby introducing an alternative focus area of HRI. This will be followed by highlighting research in a variety of areas central to non-dyadic HRI related to research with robots in various application areas and configurations. Furthermore,

2.1 Robot Definitions

This section highlights a selection of existing robot definitions, namely of social, collaborative, and service robots. Furthermore, it will highlight selected attempts at forming a generalisable definition of the term 'robot'. The existing robot definitions focus on a wide variety of aspects such as context (e.g., industrial robots), the behaviour of the robot (e.g., social or collaborative robots), or even material (e.g., soft- or software robots). Even though the presented definitions attempt to increase specificity to the broad concept of a 'robot', they all leave room for ambiguity and freedom of interpretation. Each here presented definition acts as inspiration for the robot understanding used in this dissertation (see Section 1.1). Lastly, I want to emphasise that I by no means attempt or claim to present a generalisable definition that works in every context.

The first definition of a robot I want to highlight is the definition of a *social robot* by Bartneck and Forlizzi [9] from 2004. Here they present the following definition:

Social Robot *"A social robot is an autonomous or semi-autonomous robot that interacts and communicates with humans by following the behavioural norms expected by the people with whom the robot is intended to interact."* [9]

This definition specifies a type of robot and not the term 'robot' in general—in this case, the focus is on *social* robots. While most definitions focus on the application area in order to narrow the understanding of what a particular type of robot is (e.g., industrial or delivery robot), the definition of a social robot focuses not on a context but on the behaviour of the robot. The focus here is on how the robot communicates with and behaves around people. This definition defines what a social robot is, while simultaneously attempting to delimit and describe what a social robot is not. For instance, according to this definition a fully remote-controlled robot (e.g., certain types of drones) is *not* considered a *social* robot even though it might otherwise be considered a robot, depending on the applied definition. Furthermore, this definition excludes robots that only interact with other digital artefacts, as these are robots without Human-Robot Interaction and therefore can not be considered social robots. This definition implies a physiological embodiment [9]. Inspired by this definition, I also consider the need for a physical embodiment a requirement for the device to be considered a robot. Thereby I delimit myself from e.g., software robots which are not considered in the context of this dissertation.

(a) Paro **(b)** Pepper **(c)** ABB GoFa **(d)** Baxter

Figure 2.1: The two social robots Paro (Figure 2.1a) and Pepper (Figure 2.1b) as well as the two collaborative robots ABB GoFa (Figure 2.1c) and Rethink Robotics Baxter (Figure 2.1d).

Two concrete examples, of social robots are Paro [84] (see Figure 2.1a) and Pepper [92] (see Figure 2.1b). While they have been researched in a variety of domains (e.g., elder care [58, 70] or public spaces [1, 14, 26, 93]), they both adhere to the behavioural norms expected in the given context and by the intended interaction partners. The Paro robot, for instance, has frequently been investigated in the context of retirement homes and therapy. It is designed with the intention to provide companionship—not unlike a pet—which it supports with its non-threatening design and behaviour. It has been shown that animal companionship can be beneficial in increasing the well-being of people [135], yet the use of real animals is not always possible. To substitute for this type of companionship, robots such as Paro have been investigated to demonstrate social robots capabilities indeed can substitute animal companionship in the context of therapy or elder care. A second example of a social robot utilising locomotion is the anthropomorphic social robot Pepper [92]. Daczo et al. [26] investigate if the anthropomorphic social robot Pepper could act as a guide for museum visitors. To approach visitors, the robot used human greeting behaviour akin to a human, leading to a high acceptance of the robot as a guide. Along the same lines, the social behaviour of the robot resulted in people treating it as a human interaction partner.

A different approach was taken for the definition of the 'collaborative robot' (cobot) by Peshkin and Colgate, first presented in their US patent from 1997 [25]. The patent defines a collaborative robot as the following:

Collaborative Robot *"A collaborative robot (Cobot) is an apparatus and method for direct physical interaction between a person and a general purpose manipulator controlled by a computer."* [25]

This definition takes onset in the two criteria of 'allowing direct physical interaction' and the hardware requirement of having a 'general purpose manipulator'.

Specific examples of collaborative robots are the ABB GoFa (see Figure 2.1c) or the Baxter robot by Rethink Robotics (see Figure 2.1d), and while both are typically used in the industrial context, they differ in terms of specific capabilities and interaction capabilities. The ABB GoFa for instance, optimal for tasks such as pick-and-placing, has a physical appearance inspired by classical industrial robot such as typically used in car manufacturing. However, it differs greatly in force and speed capabilities, leading to the possibility for the removal of the cage. This, in turn, allows for close-range interaction with the collaborative robots, changing the relationship between cobot and human workers. A different approach is the collaborative robot Baxter. In contrast to the GoFa robot, Baxter's strength is its capability for a higher level of expressiveness through facial expression due to its attached tablet. Furthermore, its two manipulators allow for a different type of task completion.

The third definition I want to highlight is the definition of a 'service robot' by the International Organization for Standardization (ISO) and used by the International Federation of Robotics (IFR). The ISO defines a service robot as the following.

Service Robot *"A service robot is a robot that performs useful tasks for humans or equipment excluding industrial automation applications."* [34]

The definition of a service robot is based on two criteria. Firstly, the requirement for the robot to perform a service that is perceived *useful* for humans or equipment, and secondly, this can *not* happen in the industrial context. Just as with the other robot understandings mentioned in this section, this definition leaves room for ambiguity and interpretation. For instance, the definition does not address the need—or the need for absence—of movement and/or locomotion.

An example of a service robot utilising locomotion are delivery robots (see Figure 2.2a), which are increasing in distribution, or lawn mowing robots such as presented in Figure 1.1b. As evident from the type of robot, the task they perform (i.e., delivering and lawn mowing) is a task traditionally performed by humans. This outsourcing of mundane tasks presents a certain usefulness outside of the industrial sector, thereby abiding by the definition presented above. While both these examples of robots are capable of locomotion, this is by no means a necessity given the presented definition. An example of a service robot not utilising locomotion, is the barista robot (see Figure 2.2b) by Moton Tech[1] who use robots by Jaka to

[1]https://www.motontech.net/moca/

(a) Delivery robot

(b) Robot barista

Figure 2.2: Two examples of service robots with different capabilities and service they provide.

automate the process of serving coffee. The type of robot used (i.e., the Jaka) is typically associated with collaborative robots. The reason it is, as part of the Moton Tech MOCA barista, listed as a service robot, is due to the task it performs. The switch from the industrial to the service sector allows the Jaka to be utilised as a service robot, fulfilling a task that is typically performed by humans.

The three definitions above are all attempts to delimit specific types of robot, either by behaviour, task-focus, or capabilities. Yet attempts to provide general definitions of the term 'robot' exist. I will here present two examples of general definitions of the term 'robot', by IEEE and the founder of Rethink Robotics Rodney Brooks. Both definitions, while not identical, are based on the same four factors; i) autonomy, ii) sensing of the environment, iii) computational abilities, and iv) the ability to impact its surroundings. The first definition by IEEE:

Robot 1 *"A robot is an autonomous machine capable of sensing its environment, carrying out computations to make decisions, and performing actions in the real world."* - IEEE [45]

Secondly, Rodney Brooks, the founder of Rethink Robotics, defines robots as:

Robot 2 *"A robot is some sort of device which has sensors, which senses the world, does some sort of computation, decides on an action and then does that action based on the sensor input which makes some change out in the world outside it's body."* - Rodney Brooks, Rethink Robotics [45]

Just like the definition applied in this dissertation, see Section 1.1, these also take their onset in the sense-plan-act paradigm [10] of robot definitions. Both definitions presented above emphasise that the robot needs to be able to sense its surroundings, process the data to make a decision on what to do next, and follow this up with an action that in some way affects the world surrounding the robot.

As these definitions highlight, defining a term such as robot in a generalisable way is most likely impossible. 'What a robot is' is highly context-dependent and always leaves room for interpretation and ambiguity. Therefore, while there might exist as many definitions as different types of robots, this dissertation will—inspired by these existing definitions—rely on the understanding of a robot presented in Section 1.1:

> *'A robot is a physically embodied artificially intelligent agent that can take actions that have effects on the physical world.'* [48]

2.2 Human-Robot Interaction Research

The idea of humans interacting with robots was first presented by by Isaac Asimov over 80 years ago in his novel *I, Robot* [42, page 207]. In it, he presents the three laws of robotics—which have inspired several fictitious robots—and which have been attributed as the first explicit formalisation of the need to formalise rules for the interaction between humans and robots. While this was the starting point for explicitly identifying how humans and robots should interact and co-exist, it was by no means the last attempt to develop guidelines, rules, and classifications for Human-Robot Interaction. While the here presented taxonomies present guidelines and frameworks for the classification of different aspects of HRI research—such as interaction modalities or ratios between different types of interaction partners—classifications address the categorisation of a specific set of publications. This can be informed by taxonomies or elements thereof.

In this section, I will present selected existing taxonomies to classify Human-Robot Interaction research. Furthermore, I will highlight current efforts in the classification of non-dyadic HRI research. Thereby, I highlight not only existing research but further emphasise the breadth of research within the interdisciplinary field of Human-Robot Interaction.

2.2.1 Taxonomies

To classify current efforts in Human-Robot Interaction into a common taxonomy of terms and concepts for the field a series of different taxonomies and frameworks have been created (e.g., [22, 43, 79, 131, 136, 137]). Yanco and Drury [137] created their first taxonomy centring around six concepts. Their taxonomy takes its onset in terms originating from the two related fields of Human-Computer Interaction (HCI) and Robotics (see Figure 2.3). Some of these form a spectrum, e.g., *Autonomy Level / Amount of Intervention* which ranges from 'Teleoperated' to 'Fully autonomous', others rely on discrete categories. The second concept is related to the *ratio between people and robots*, ranging from dyadic to multiple different non-dyadic configurations. Here the taxonomy focuses on eight different configurations in which human(s) and robot(s) can interact with each other. These range from focusing on the dyadic setting (e.g., [57, 86]), one human interacting with a multiple robots (e.g. [83, 138]), multiple humans interacting with one robot (e.g., [106, 114]), to depicting a group of humans interacting with a group of robots (e.g., [130]). The distribution of ratios that are part of the taxonomy further highlights the complexity of non-dyadic HRI as seven out of the eight configurations are addressing various configurations related to non-dyadic Human-Robot Interaction. The fifth concept of the taxonomy is the time and space taxonomy. It is addressing the relationship between human(s) and robot(s) in time and space, leading to four distinct combinations of when and where the interaction can happen, namely collocated:synchronous, collocated:asynchronous, non-collocated:synchronous, or non-collocated:asynchronous[2]. The last concept I want to highlight is related to the *composition of robot teams*. It addresses types of robots in group configurations in which multiple robots can, according to [137], be either homogeneous or heterogeneous. I argue, that the classification of the robot composition into homogeneous and heterogeneous, while being useful, might benefit from being placed along a spectrum instead of being a binary choice. As there might be differences in how we interact with a group of robots which has two different kinds of robots while simultaneously having multiple of each, compared to a group with multiple different robots.

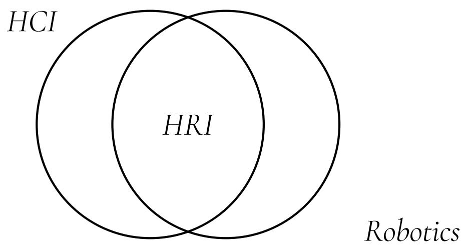


Figure 2.3: Yanco and Drury [136, 137] used the fields of Human-Computer Interaction and Robotics as foundation to create their Human-Robot Interaction taxonomy.

Yanco and Drury expanded on their taxonomy in 2004 [136] and added five additional concepts (making it a total of eleven). The added concepts are related to the type of tasks the robot(s) work on, the robot morphology—as we might interact differently with a robot depending on if it is embodied in an anthropomorphic, zoomorphic, or functional way—level of shared interaction amongst human team members, variety in roles human team members can take (e.g., supervisor or operator), as well as the differences in proximity between human(s) and robot(s) in the group. This taxonomy can help to make conscious decisions about types of robots and their interaction, and thereby help to inform future design choices when designing and developing robots.

[2]Alternative terms used for asynchronous and synchronous are sequential and simultaneous respectively. Alternative term used for non-collocated is remote.

A more recent approach to the creation of a taxonomy for HRI was taken by Onnasch and Roesler [79]. They structure their framework around three clusters (interaction context, robot, and team classification) with multiple categories and characteristics in each, and while some share characteristics with previously mentioned taxonomies (e.g., robot morphology [136]), it adds some distinguishing features. For instance, while the framework—as many others [101,105,137]—consider the characteristic of 'team composition' the meaning is not the same. Onnasch and Roesler do not distinguish between individual quantities but between the ratio between the robots and humans. Here, three different compositions exist, namely equal number of humans and robots ($N_H = N_R$), more humans than robots ($N_H > N_R$) and more robots than humans ($N_H < N_R$). Differentiating this framework from other alternatives mentioned is the focus on specific context, or field of application, including such common areas as 'industry' [98]), 'military' [18], or 'education' [55]. The question, what a robot is and how to appropriately interact with it depends to a large degree on the contextual circumstances, as highlighted with e.g., the coffee barista robot presented in Section 2.1. Additional characteristics of the framework are inspired by existing work on different levels of autonomy [82] used to distinguish between the robot's ability of information acquisition, analysis, decision-making, and action implementation. With this, the framework incorporates a tool to measure the implementation of the sense-plan-act paradigm on which several understandings of the term robot are built.

2.2.2 Classifications

Inspired by the taxonomies above, a number of literature reviews and classifications of existing research within HRI have been conducted [33, 90, 101, 105]. These classifications of existing research, help organise the field of HRI and can be used to identify areas of particular interest, or lack thereof, within the field.

A recent review on research within Human-Robot Interaction has been done by Sebo et al. [105]. They generate an article corpus of 103 papers describing non-dyadic HRI studies. Using several of the concepts presented by Yanco [136] they classify the published non-dyadic HRI research along a multitude of characteristics including morphology, the degree of autonomy (or use of Wizard of Oz), as well as the robot's behaviour (e.g., locomotion, gaze, or gesture capabilities) to mention some criteria investigated. Furthermore, they used different configurations to characterise different human-to-robot ratios. Their findings show that the vast majority of Human-Robot Interaction research is focusing on the investigation of multiple humans, primarily two people or a crowd, interacting with a single robot. In the same manner, they can identify that the concept of embodied morphology [136], focuses heavily on anthropomorphic robots. A total of 83% of the corpus investigated [105] focuses on robots with anthropomorphic features, specifically a head and eyes (e.g., Emys [77] or Keepon [96, 106]). The taxonomy by Yanco [136] highlights interaction role as a key feature for Human-Robot Interaction and specifies five different roles the human can take in relation to the robot (supervisor, operator, teammate, mechanic, or bystander). The view of the existing HRI literature [105], while using role as a factor, looks at the *robot's* and not at the human's role. Here, they distinguish between three different categorisations, namely leader, peer, or follower.

Another review of existing research was conducted by Laurel Riek [90]. The author synthesised 54 studies utilising Wizard of Oz (WoZ) methodology, in order to develop guidelines on how to report on WoZ studies. They propose a greater methodological thoroughness when conducting and reporting WoZ studies, thereby increasing the rigour and comparability of this method. Furthermore, the paper quantifies and exemplifies the types of shortcomings in the reporting of WoZ studies, such as the lack of reporting of wizard errors

2.3 Dyadic Human-Robot Interaction

While this dissertation focuses on aspects of non-dyadic HRI, this section's purpose is to provide a brief overview of selected dyadic research of HRI. The field of HRI has been characterised by a predominantly focus on dyadic research [101], i.e., research investigating some aspect of *one* human interacting with *one* robot. Topics include human-robot trust [19,31,49], assistance for elderly [41], verbal interaction with robots [30], or expressivity of robot motion [3, 107, 140].

A study by Sirking et al. [107] investigated whether non-anthropomorphic and non-verbal robots are able to engage people in interaction purely through the use of motion and gestures. For this, the authors developed a robotised ottoman capable of locomotion as well as slight up and down movement. Using a qualitative lab-based wizard-of-oz user study, they evaluated the ottoman's capability to engage unsuspecting participants to interact with it. Specifically, the robotic piece of furniture attempted to, only using locomotion, convince the participants to rest their feet on top of it (which succeeded for 14/20). Likewise, the 'please remove your feet' motion—namely a quick raising and lowering—was successful in conveying the ottoman's intent. This study demonstrates, that a high level of specificity and expressivity can be reached through motion alone. Furthermore, for robots to successfully engage people in interaction, neither verbal communication nor anthropomorphic embodiment is necessary.

Another classic area of dyadic HRI is the investigation of trust in robots as collaborators (e.g., [19, 31, 49, 125]). A recent study by Hald et al. [49] describes a lab study in which they investigated human trust assessment and adjustment when interacting with a robot during a drawing task. As participants were holding a piece of paper, the robot draws along a line projected onto the paper. Halfway throughout the study, the robot would suddenly change its speed, resulting in a reduction of trust. Interestingly, the trust measure following the increase in speed went up again after a few iterations, suggesting that the level of trust is related to the robots consistency.

Furthermore, the investigation of dyadic HRI has had a strong emphasis on the investigation of different aspects of HRI within controlled settings such as lab or online studies (e.g. [49, 69, 103, 107, 125]). Thiessen et al. [123] investigate how the use of infrasound, near the human-hearing threshold, can impact participants perceptions of a robot. To investigate this, the authors recruited 25 participants for a lab study in which participants would observe the NAO robot perform motion. Each participant would observe the robot perform three motions, twice with, and twice without infrasound resulting in a total of 12 trials for each participant. They showed, that valence (how positive or negative something is perceived) was increased significantly through the presence of infrasound. Meaning that the presence of infrasound makes the robot appear more positive.

2.4 Non-Dyadic Human-Robot Interaction

The amount of Human-Robot Interaction research has increased over the years, and while robots are still a somewhat new reality, the deployment often starts in seemingly complicated domains such as industry or even space exploration. As Cynthia Breazeal puts it:

> *"If you look at the field of robotics today, you can say robots have been in the deepest oceans, they've been to Mars, you know? They've been all these places, but they're just now starting to come into your living room. Your living room is the final frontier for robots."* - Cynthia Breazeal (as presented in [78])

As the quote above states, robots have reached an abundance of different domains including space, the bottom of the sea, and everything in between. Cynthia Breazeal here postulates that 'the final frontier' for robots is the living room. But why is it, that a seemingly simple domain—when compared to e.g., outer space—such as private households is being referenced as the last frontier for HRI. For this, we can observe two reasons. Firstly, the sheer abundance of private households makes it hard to guarantee that deployed robots work in every one of them. Robot deployment in a context such as the home is complicated by the physical environment (which is very diverse and hard to control), the abundance and diversity of different devices with which the robot(s) has to function, as well as the variety of different users and expertise levels. Secondly, while robots for specialised domains such as space exploration or the industrial context have to interact with a handful of people—all of which are highly trained—robots in private households have to interact with millions of novice users. This requires different levels of learnability and robustness from the robot depending on the context of deployment.

In this section, I will present non-dyadic research using two specific lenses. Firstly, I will present selected research through the lens of two different non-dyadic HRI ratios. Secondly, I will give examples of non-dyadic HRI research based on the different types of robots (Section 2.1) and their predominant application domain. Together, these two lenses act as introduction to set up the context for my paper contributions (see Chapter 3).

2.4.1 Human-to-Robot Ratio

The first lens through which I will highlight some research is based on the concept of the human-to-robot ratio. Specifically, this section presents selected non-dyadic HRI research within the two categories i) research involving *multiple robots* and ii) research involving *multiple humans*.

Multiple Robots as part of the Interaction

HRI research investigating interaction in multi-robot scenarios has had a wide variety of focal points such as the robots perceived warmth and competence [76, 77], relation to robots depending if they are competitors or collaborators [52], trust in robots [40], telepresence or teleoperation [139] robot groups ability to influence humans [96], or how robots affect human behaviour and collaboration [66].

Salomons et al. [96] investigate if people are willing to conform to groups of robots, even though they might think their answer is incorrect. To investigate robot group potential to impact decision-making behaviour, the authors conducted a lab study in which individuals interact with a group of Keepon robots. Participants were asked to answer questions without an objectivly correct answer. While the control group was not able to see the robots' answers before selecting, the experimental group could see the robots' choice before making a selection themselves. Results show, that participants in the control condition, changed their preliminary response to a significantly higher extent in order to conform to the robots' answers compared to the control group. Thereby, the authors provide evidence for the occurrence of humans conforming to groups of robots.

Leite et al. [66] investigate the impact of individual or group learning sessions on children's ability to recall a narrative as well as correctly identify the emotional state of a character (emotional understanding). Through the interaction with two robots, one of which the children could control, the individual or group of children would experience three interactive narratives. Results from the study show that while children experiencing the story by themselves are better at recalling the narrative details, no significant effect on the emotional understanding of the children was identified.

Multiple Humans as part of the Interaction

A multitude of research has investigated how robots as part of multi-human groups affect the way we interact with robots and collaborate with other group members [72, 85, 106, 114, 115]. A study by Shen et al. [106] investigates how a social robot, the Keepon, can help pairs of children to develop conflict resolution skills. Pairs of children were matched up around a selection of toys, whenever an object possession conflict was observed Keepon would utilise three distinct steps to help the children resolve the conflict in a constructive manner. Upon detection of a conflict, Keepon would indicate the onset of the conflict using a whistling sound, following which the Keepon would propose ways the children could resolve the conflict (e.g., playing with the toy together or communicating what each child wants to achieve). The authors showed, that while conflicts happened in both the mediation and the control condition, children were more likely to resolve conflicts in a constructive manner when supported by Keepon.

To investigate how to efficiently include team members in mixed human-robot teams, Sebo et al. [114] conducted a study in which a triad of humans interacts with the social robot Jibo (Task B). Prior to interacting in a triadic setting with the robot, the triad was divided into a dyad and a one-person group each solving, together with a Jibo robot, the dessert survival task (Task A). Following Task A, the three collaborators were collaborating to narrow the list of items—for the dessert survival task—further down. This was done with the help of Jibo. The authors compared two conditions, a) (ingroup member) a member of the dyad was the only one who in Task B could interact with Jibo and b) (outgroup member) the member from the one-person group was the only one able to interact with Jibo during Task B. Findings showed, that when the outgroup member was the only one able to interact with the robot, the items proposed by the outgroup and robot were less likely to make it to the final list compared to when an ingroup member was interacting with the robot. For condition b), the fact that only the outgroup member could interact with the robot strengthened the feeling of excluding the outgroup member from the group collaboration.

While the previous two studies present different impacts on human-human collaboration through robots, an alternative to this was investigated by Pelikan et al. [85]. The authors investigated the impact of robot introduction in an operating room. Specifically, they investigate how the introduction of the da Vinci Surgical System robot affects collaboration and relations between team members present in the operating room (e.g., surgeon, assistants, and nurses). They present evidence highlighting that the introduction of the surgical robot lead to a reconfiguration of spatial configurations within the operating room, thereby affecting the distances between team members and ultimately changing the way the team collaborates. This reconfiguration of spatial distribution affects both the *physical, cognitive* and *affective* distance between team members, changing the way in which team members can monitor each other and rely on each other's skills, which is vital for a successful operating outcome.

These three examples highlight robots' capabilities to affect how humans collaborate with each other in a variety of contexts. While all three examples include multiple humans, from pairs to groups, the relationship and collaboration between these are affected by changes due to the robot introduction.

2.4.2 Types of Robots

This section presents selected HRI research through the second lens, namely robot type and application area. Here, I highlight three different robot types in four different application areas. This selection is based on the three different definitions of robots presented in Section 2.1, namely social, collaborative, and service robots, thereby representing a wide selection of different robots and domains that are investigated within the field of Human-Robot Interaction. The intention with this section is two-fold. Firstly, by presenting HRI research on various types of robots and domains, I demonstrate the breadth of the interdisciplinary field that is HRI and secondly, by highlighting specific application areas in relation to robot types I introduce relevant literature for the paper contributions presented in Chapter 3.

Social and Service Robots in the Home

The home is a typical anchor point for several different types of Human-Robot Interaction research, namely interaction with social and service robots. Given the personal setup and configuration of different homes and devices, the private home represents a potentially chaotic and unstructured environment. Furthermore, the domestic context, and the interaction with robots and other devices in it, represent an interaction with diverse novice users who have no specific training in how to efficiently interact with the robots or how to collaborate with other household members to facilitate the robots. Previous research has attempted to identify characteristics of 'who' domestic service robot owners are [116]. Results showed that this type of service robot in the home is equally likely to be adopted by both men and women, but robot owners tended to be younger, with a high level of education and a good technical understanding. Forlizzi and DiSalvo [36] investigated how the introduction of an early model of the Roomba changed how households performed the task of cleaning. They could show, that the addition of the robotic agent, amongst others, turned the activity of cleaning into a social activity which required collaboration amongst different members of the household collectively 'pre-cleaning' individual areas of the environment to facilitate the robot. Additionally, they argue that the interaction with robots in the home is a process that requires mutual coordination within the spatial environment. For instance, some households used objects to prevent the robot from going places it was not supposed to go to.

While the domestic robot market is dominated by service robots performing cleaning tasks, alternative types of robots have been investigated—social robots. Examples of the use of social robots include robots used to combat loneliness [59], smart home control [69], therapy sessions for children with ASD [99], or for home teaching [50]. In a study by Jeong et al. [59] the authors utilise three Fribo robots, one for each participating one-person household, in order to combat loneliness. Fribo would inform the other two households in each household triad of sensed living noises, such as when cooking or opening the washing machine, thereby providing each member in the household triad a sense of presence and awareness of the other households. The real-time presence of living noise representing the other households, created the feeling of a virtual living space shared amongst the three households, resulting in the feeling of closeness amongst participating households, thereby reducing loneliness. Luria et al. [69] conducted a comparative lab-based study comparing three devices, including an embodied social robot, and the device's impact when managing an IoT home. They showed that while the interaction with the robot yielded the most enjoyable home management system and was the easiest to recall—since the robot's state was visible at all times, this was not without drawbacks. Users perceived the usability of the robot for smart home management to be lower compared to more traditional smart-home control interfaces such as apps or wall-mounted displays. Lastly, the robot provided the highest situational awareness among the compared interfaces.

Collaborative Robots in Industry

Collaborative robots and other types of industrial robots have been investigated with a multitude of focus points such as the investigation of perceptions towards industrial robots [98, 103], programming of industrial robots [112], the impact of cobot implementation on manual work [68], as well as potential threats and opportunities industrial robots can bring [109].

With the increased focus on robotisation of the industrial sectors, the media has often reported robots as a potential threat that can steal jobs [13, 120]. Contrasting this, Smids et al. [109] investigated the increasing automation of the industrial sector using robots through a more nuanced lens. Smids et al. focus on the impact of increased robotisation on workers' perception of doing meaningful work, which ultimately leads to better worker well-being and higher job satisfaction. Through a literature review, they identify five unique dimensions that contribute to the feeling of completing meaningful work, including autonomy as well as social relationships in the workplace. Following, they hypothesise how each of these five dimensions can contribute—both positively and negatively—to the workers feeling of doing meaningful work in a robotised workplace. Amongst these, the possibility for an increase in social interaction—which might seem counterintuitive—is one possibility. Furthermore, social interaction could be affected positively, if industrial robots to a higher extent, than currently, were able to engage in social interactions. The robot's ability, if introduced in a way that emphasises opportunities over threats, to remove tedious and repetitive tasks from the workers, will allow closer collaboration between workers on higher complexity tasks. Thereby, industrial robots could contribute to increasing the feeling of meaningful work amongst workers. Sauppe and Mutlu [98] investigated how industrial workers perceive a collaborative robot with anthropomorphic features—the Baxter robot. This includes consideration of physical characteristics (e.g., appearance) as well as its social behaviour and capabilities on the manufacturing floor. Using a qualitative approach utilising observations and interviews, Sauppe and Mutlu identify four themes related to workers' impressions. For instance, while workers already engaged in social interaction with the Baxter robot, they expressed the desire for the robot to have even greater social capabilities, as also mentioned by Smids et al. [109].

Social Robots for Rehabilitation, Elder Care, and Education

Non-dyadic HRI has for long been investigated in the context of rehabilitation [46]and elder care [51, 53, 95]. With the anticipated increase in the global population older than 65 [74], finding ways to support this generation without increasing the need for human personnel becomes increasingly relevant. To address the staff shortage in physical therapy for older adults, Hebesberger et al. [53] conducted a longitudinal study using the mobile non-humanoid SCITOS G5 robot. The robot was accompanying four group walking sessions each week, with 4-5 elderly and 2 therapists per walking group, for the duration of one month. Its multimodal nature, such as combining situated sounds and visual material, enhanced the walking experience. Especially in terms of providing entertainment value for the elderly during the walk, the robot was perceived as helpful.

To investigate robot support rehabilitation, Özgür et al. [46] developed the Cellulo platform. A small-sized graspable robotic platform utilising haptic signals. Through a participatory design approach and eight iterations, they develop a game-based approach using collaboration between the therapist and patient when interacting with the robot, in order to motivate patients throughout the rehabilitation process. They show, that tangible robots as rehabilitation support can contribute to the performance of more precise rehabilitation exercises, thereby positively affecting the engagement (i.e., time spent performing rehabilitation exercises) as well as the accuracy of user motion.

Within HRI a large emphasis has been placed on the teaching domain including second language learning [27], writing skills [55, 97], child engagement [47], or conflict resolution [106]. Just as it is the case for the rehabilitation and elder care context, the tutoring context is predominantly characterised by the use of social robots.

A study by Hood et al. [55] has investigated how groups of children collaborate around the task of teaching handwriting to the social humanoid robot NAO. To evaluate the effectiveness of the robot supported learning-by-teaching approach investigated in this paper, the authors highlight the need for longitudinal studies. However, the two studies presented in this paper already provide an indication that a humanoid robot is capable of acting as a student, resulting in high levels of engagement from the children. Lastly, the authors highlight the robot's unique capabilities—compared to peers or adults—to act as a believable naïve learner for the children. Gvirsman et al. [47] investigate how to engage both toddlers and parents (or caregivers) in toddler-parent-robot triads using a toddler-friendly educational robot. They develop a robotic platform, Patricc, which emphasises customisability in order to provide continuous novelty, thereby leading to better opportunities for long-term engagement. By including the parent as an active interaction partner, they showed that the interaction with the robot Patricc leads to a higher degree of actual triadic interaction when compared to e.g., tablet-based alternatives. Both the parent and Patricc interact with the toddler in a triad, whereas in a tablet-based scenario the tablet typically attracted most of the toddler attention, leading to a reduced toddler-parent dynamic.

2.5 Summary

In this section, I started out by presenting a multitude of different understandings and definitions of specific types of robots leading to the in this dissertation used understanding of the term 'robot'.

> *'A robot is a physically embodied artificially intelligent agent that can take actions that have effects on the physical world.'* [48]

Following this, I have presented existing frameworks and classifications presenting different attempts at structuring the vast and interdisciplinary field of HRI. Furthermore, I briefly outline dyadic HRI, thereby highlighting the scope of HRI beyond my focus area in this dissertation. In order to illustrate two different lenses through which one can investigate the field of HRI, I present related work through the two lenses of 'human-to-robot ratio' and 'different types of robots' based on the presented definitions. These two sections further contribute to presenting the breadth of the interdisciplinary field of non-dyadic HRI. With this section, I attempt to give the reader an overview of existing research as well as outline the context for the following chapters and the paper contributions as part of this dissertation.

3 PAPER CONTRIBUTIONS

In this dissertation, I investigate the characteristics of non-dyadic Human-Robot Interaction research, and how it influences collaboration during non-dyadic Human-Robot Interaction. To structure this research effort, I formulated two research questions, as presented in Section 1.4. To answer these research questions, I conducted five studies focusing on different aspects of non-dyadic HRI. The five resulting papers, which will briefly be described in this chapter, constitute the primary contribution of this dissertation. The five papers can be found in the Appendix.

1. **Eike Schneiders**, EunJeong Cheon, Jesper Kjeldskov, Matthias Rehm, and Mikael B. Skov. 2022. Non-Dyadic Interaction: A Literature Review of 15 Years of Human-Robot Interaction Conference Publications. *ACM Transactions of Human-Robot Interaction (THRI)*. 11, 2, Article 13 (June 2022), 32 pages. https://doi.org/10.1145/3488242

2. **Eike Schneiders**, Anne Marie Kanstrup, Jesper Kjeldskov, and Mikael B. Skov. 2021. Domestic Robots and the Dream of Automation: Understanding Human Interaction and Intervention. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 241, 1–13. https://doi.org/10.1145/3411764.3445629

3. EunJeong Cheon, **Eike Schneiders**, and Mikael B. Skov. 2022. Working with Bounded Collaboration: A Qualitative Study on how Collaboration is Co-constructed around Collaborative Robots in Industry. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

4. EunJeong Cheon, **Eike Schneiders**, Kristina Diekjobst and Mikael B. Skov. 2022. Robots as a Place for Socializing: Influences of Collaborative Robots on Social Dynamics In- and Outside the Production Cell. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

5. **Eike Schneiders**, Stanley Celestin, Christopher Fourie, Guy Hoffman, Julie Shah, and Malte Jung. 2022. Understanding Entrainment in Human Groups: Identifying Cobot Design Considerations based on Human Collaboration.

3.1 Paper I - Characteristics of Non-Dyadic HRI Research

Paper I

Eike Schneiders, EunJeong Cheon, Jesper Kjeldskov, Matthias Rehm, and Mikael B. Skov. 2022. Non-Dyadic Interaction: A Literature Review of 15 Years of Human-Robot Interaction Conference Publications. *ACM Transactions of Human-Robot Interaction (THRI)*. 11, 2, Article 13 (June 2022), 32 pages. https://doi.org/10.1145/3488242

With the increase of Human-Robot Interaction in groups containing both humans and robots, numerous studies (e.g., [4, 37, 38, 39, 59, 66, 76, 77, 126]) have called for an increased focus on non-dyadic HRI research. Oliveira et al. [76] referred to this shift in attention from dyadic to non-dyadic HRI as a 'paradigm shift'. Yet, a comprehensive overview of the characteristics, trends, and tendencies of past non-dyadic Human-Robot Interaction research has been lacking. Such overviews have the potential to highlight gaps in existing research, increase awareness of single-sided research within a research community, as well as identify future directions for research. To identify tendencies and directions within non-dyadic HRI, as well as to present empirical evidence of this hypothesised paradigm shift toward non-dyadic HRI, we conducted a literature review.

In this paper, we present a literature review based on all full papers published at the *'IEEE/ACM International Conference on Human-Robot Interaction'* from its creation in 2006 until 2020, both years included, to construct a comprehensive overview of contemporary HRI research. As we were interested in identifying characteristics of non-dyadic interaction, we started out by defining 'Non-Dyadic interaction in HRI' as the follows: *"Non-dyadic interaction in HRI is any interaction involving at least one physical independent digital artefact — at least one must be an embodied robot — AND at least one human. Either party (artefact OR human) has to be more than one."* [101]. In line with the understanding of a robot in the context of this dissertation (see Section 2.5) we emphasised the need for *physically embodied* digital artefacts, thereby excluding e.g., software robots. Inspired by existing research [110, 136, 137], the first contribution of this paper is the specification of three non-dyadic configurations, namely:

1. *One-to-Many:* One human interacts with multiple digital artefacts, of which at least one is an embodied robot.
2. *Many-to-One:* Multiple humans interact with one embodied robot.
3. *Many-to-Many:* Multiple humans interact with multiple digital artefacts, of which at least one is an embodied robot.

Using this definition we narrowed the paper corpus down to 164 HRI Conference publications. To characterise different interaction principles, such as remote interaction or extension, we utilised an existing framework for classification of multi-user and multi-artefact interaction [110]. We made several modifications to the framework to accommodate the changed context towards non-dyadic HRI. This included, amongst others, the re-definition of the principle 'Collaboration' to 'Coaction', as the original framework did not consider collaboration between human(s) and device(s) (e.g., robots) to be collaboration. Furthermore, the framework lacked specificity in terms of describing individual interaction. While it focused on the two non-dyadic dimensions of "Many Users" and "Many Artefacts", these were not sufficient to categorise interaction into the three aforementioned non-dyadic configurations. The revised framework uses the same temporal axis (simultaneous and sequential) on the x-axis and the three configurations of one-to-many, many-to-one, and many-to-many on the y-axis.

The paper, makes three specific contributions. Firstly, by analysing this extensive corpus of non-dyadic Human-Robot Interaction research we were able to map research into a matrix of interaction principles (based on our modified framework) and the three created non-dyadic HRI configurations. Thereby we were able to highlight focus points of Human-Robot Interaction, including the heavy focus on HRI utilising simultaneous—over sequential—interaction in groups. Furthermore, we provided empirical evidence towards the hypothesised paradigm shift [76], as the share of non-dyadic HRI research increased from 8% in 2008 to 36% in 2020. Secondly, by modifying an existing framework for non-dyadic interaction in order to increase its applicability to HRI, we provide an updated—HRI specific—framework for the classification of different types of interactions and configurations. This framework acts as a mapping of existing research within a multitude of constellations. Lastly, we highlight future directions for the HRI community as well as present open questions for future investigation. Example topics for future research include the investigation of the impact of different interaction techniques—as presented in the modified framework—on user experience in HRI, as well as the investigation of how different interaction principles affect the flow of non-dyadic HRI.

This paper contributes by investigating characteristics and trends within non-dyadic Human-Robot Interaction research.

3.2 Paper II - The Dream of Automation: Robots in the Home

Paper II

Eike Schneiders, Anne Marie Kanstrup, Jesper Kjeldskov, and Mikael B. Skov. 2021. Domestic Robots and the Dream of Automation: Understanding Human Interaction and Intervention. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 241, 1–13. https://doi.org/10.1145/3411764.3445629

With robots entering our homes and private spaces (e.g., [29, 36, 59, 102, 111, 132]), an understanding of how household members interact with this new type of domestic technology becomes increasingly important. Domestic robots not only have the potential to change the way we complete and understand specific tasks but also to change the organisation and collaboration between different members of a household [59]. Furthermore, in contrast to e.g., the industrial setting, the domestic space is particularly challenging as every household, including the available digital ecology [88] that is present, varies. While HCI research has long been invested in researching various aspects of domestic robots, such as personalisation [117, 118], long-term effects [32], or the characteristics of domestic robot owners [116], little attention has been paid to how robotic automation changes routines, the behaviour of household members, social interaction, or the environment itself.

In this paper, we present an empirical field study conducted in 24 Danish households. We investigate robotic automation of everyday tasks and the changes to task completion within the household that accompany the introduction of robots in the home. With the ongoing growth of robots in various sectors, including the domestic space [12, 111], a well-founded understanding of *how* we automate and interact with this technology, and what differences it brings to our everyday life is important. We use multiple qualitative methods, including on-site contextual technology tours [7], semi-structured interviews, as well as the staging of robots in households. The semi-structured interviews were partially carried out during home visits ($N = 9$). During the contextual technology tour, interviewees elaborated on specific anecdotes and highlighted physical areas that provided challenges or interesting observations. Furthermore, this allowed participants to show and demonstrate robot(s) capabilities and elaborate on this by highlighting other aspects of their digital ecosystem, such as connected personal assistants, DIY solutions, or smartphone functionality. Additionally, we interviewed 12 households virtually. The last method employed for data collection was the staging of robots in additional households ($N = 3$). These households had no prior experience with domestic robots. This provided us with insights into novice users robot adoption. During these 10-day robot deployments, I met with the households three times—during the handout of the robot, approximately halfway through the deployment period, and on the last day. During each visit, I conducted a semi-structured interview with all members of the household. Semi-structured interviews followed a pilot-tested interview guide containing five predefined topics. Furthermore, all participating households were asked to document and share findings they considered interesting using photos and videos, resulting in over 220 pictures and videos-clips.

This paper contributes with three themes related to domestic automation using robots. Firstly, it highlights changes to human behaviour in order to facilitate efficient robot operation. While the tasks that the robot was supposed to complete was considered *one coherent* task prior to its implementation, this was no longer the case. The specific task the robot was supposed to perform was fragmented due to the robot implementation, and only part of these sub-tasks, e.g., the mowing of the lawn, was efficiently automated using the robot. Secondly, we show that the facilitation of domestic service robots requires a change in the spatial set-up, requiring the change towards a more robot-centric environment. The optimal use of robots in the home was, to the surprise of participants, often not a plug-and-play solution. It required a change of the environment, as the domestic context typically is not designed to ensure robot accessibility. Lastly, following the adaption of own behaviour and the environment, households were faced with the need to adapt their digital ecology [88]. As not all the encountered domestic robots supported connectivity with additional devices, several households used custom solutions to expand their robot's digital infrastructure, thereby adding new features to the robot(s). Furthermore, household members—at times—used other household members as proxies in order to remotely interact with the domestic robot(s).

This paper contributes with the investigation of how collaboration with domestic robots changes aspects of user behaviour, environment, and collaboration with other household members to facilitate the robot. Furthermore, automation using domestic robots changes the nature of the task that is being automated.

3.3 Paper III - Robots Influence on Collaborative Tasks

Paper III

EunJeong Cheon, **Eike Schneiders**, and Mikael B. Skov. 2022. Working with Bounded Collaboration: A Qualitative Study on how Collaboration is Co-constructed around Collaborative Robots in Industry. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

Since the introduction of the first industrial robot in 1961, the Unimate [80], the industrial context has received a lot of attention in relation to automation using robots. In recent years, this focus on automating factories by removing humans and replacing them with caged industrial robots has taken a turn towards a more human-centric focus, aiming at humans-robot collaboration for increased productivity. While a multitude of research has investigated how industrial robots are perceived (e.g., [68, 98, 103]), limited research has investigated how the introduction of industrial robots has affected the relationship between human workers or how collaboration with robots is understood by workers.

In this paper, we used a qualitative multi-method approach to investigate how the introduction of collaborative robots (cobots) affects human workers, including the role of workers' involvement when introducing the new technology, the cobot's impact on operators' job identity, the meaning of collaboration with and around the new technology, as well as the change of spatial and temporal working rhythms caused by the cobots. To investigate this, we started by familiarising ourselves with the domain-specific terminology as well as the industrial landscape through participation in 19 webinars and online workshops on topics such as efficient robot introduction or how cobots flexibility can improve overall efficiency. While this was not part of the data used for later analysis, it helped to gain an overview of the industrial context in relation to robotic automation from the companies' point of view. The collection of data consisted of two data streams, secondary and primary data. The secondary data consisted of 115 case studies from cobot manufacturers about their clients. The primary data consisted of 14 expert interviews with stakeholders related to cobots, including UX researchers at cobot companies, project managers at companies introducing cobots, technical supporters, and industrial workers. Furthermore, we visited two companies that were currently in the process of increasing automation using cobots.

This paper contributes with four findings related to the introduction of cobots in the industrial context. Firstly, our findings show that the successful adoption of cobots as new automation technology is not, as often advertised, an easy and flexible solution that improves productivity out of the box. While the technology might be quick to set up, making it feasible depends to a vast extent on how industrial workers accept the new technology that is often seen as a potential competitor to employment. Therefore, efficient cobot introduction depends not just on a top-down managerial decision, but also on the operators' willingness and involvement to interact and collaborate with and around the cobots. To achieve this, industrial workers need to be involved, and listened to, early in the introduction process—potentially already prior to the adoption of cobots—thereby effectively increasing their knowledge making them cobot ambassadors. Secondly, the introduction of the cobots led to fragmentation of tasks, resulting in human collaborators becoming 'robot supporter'. This change of job identity led to human operators collaborating with each other around peripheral tasks, changing their initial responsibilities from i.e., 'assembly' or 'metal cutting' to 'robot maintenance and preparation'. The emphasis on peripheral tasks resulted in a shift, and even loss, in perceived job identity. Employees who, prior to the cobot introduction, perceived themselves as e.g., welders, now had the responsibility for staging, preparing, troubleshooting and maintaining the cobots. Thirdly, while the concept of collaboration is often referred to as a well-defined construct—i.e., collaboration is every action between people and devices working towards the same goal, in practice, the concept of collaboration is less clear and well understood. While collaborative robots imply that these are robots with which workers can collaborate, this was rarely the case as the collaboration with robots was still limited by their level of technological advancement. Finally, the use of cobots in the industrial context changes the working spaces and rhythms at which collaboration with and around them occurs. The automation of processes using cobots, in contrast to other industrial robots that require cages, results in the possibility for closer spacing between cobot(s) and human worker(s). However, even though no cages were present around the cobots, 'virtual' walls still existed, as too close proximity to the cobots (i.e., entering their range) would result in a reduction of cobot operating speed. This led to times at which collaboration with the cobots was less optimal than at other times, thereby effectively changing how the human operators perform given tasks.

This paper contributes with an investigation of how the role of humans changes due to the introduction of cobots in the workplace. In particular focusing on changes in task completion, worker responsibilities, and working rhythms in relation to non-dyadic cobot supported collaborative work in industry.

3.4 Paper IV - Robots Effect on Interpersonal Relationships

Paper IV

EunJeong Cheon, **Eike Schneiders**, Kristina Diekjobst and Mikael B. Skov. 2022. Robots as a Place for Socializing: Influences of Collaborative Robots on Social Dynamics In- and Outside the Production Cell. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

Robots as a means for increased efficiency have gained increased popularity within sectors such as production and manufacturing. However, previous studies have shown that the introduction of robots can result in unintended side effects such as changes to the spatial distribution of workers or interpersonal relationships between collaborators [60, 65, 85, 109]. Yet, we have a limited understanding of the broader consequences that the introduction of this new automation technology, i.e., robots, has on the daily workprocesses, organisational structures, or interpersonal relationships between people in- and outside of the production cell. Smids et al. [109] hypothesise that the introduction of robots into workplaces, in contrast to popular belief, can improve interpersonal relationships.

In this paper, we used a qualitative approach based on 14 interviews with six industrial workers over the course of three months in a large Danish production company. Each operator participated in one to three interviews, dependent on worker availability. The interview guide was structured around four topics relating to changes in the company's production processes with the introduction of cobots, including changes in tasks, work routines, social interactions, and workers' involvement in integrating the cobots in the workplace [20]. Furthermore, weekly visits in the production cell increased understanding of the industrial workers' day-to-day operations. Through the use of constructivist grounded theory [16, 17] three themes emerged from data. These themes are structured through the lens of spatial arrangement, leading to an organisation of themes based on spatial relation towards the production cell, i.e., collaboration within the cell, collaboration between different shifts working in the same cell, and collaboration reaching outside of the cell.

This paper contributes with three findings on worker-centred HRI in the industrial context. These are related to the i) reorganisation of the production process from pipeline to production cell, ii) cobot-related information distribution across different shifts, and iii) interaction and relationship with colleagues outside of one's own production cell. Firstly, the introduction of cobots into industrial manufacturing processes required a spatial restructuring of the production pipeline towards a circular layout as part of a production cell. While this had consequences for the number of workers per cell—being reduced from four to two/three—this, surprisingly, had a beneficial effect on the perceived quality and quantity of social interaction between operators. Due to the introduction, and thereof resulting spatial restructuring of the physical work environment, social interaction and collaboration amongst workers in the cell improved. Thereby, we were able to confirm Smids et al. [109] hypothesis. Secondly, while limited information was provided on how to efficiently collaborate with the new technology, this information was not distributed evenly amongst workers. Differences in working shifts added additional barriers in relation to information availability. The night shift, for instance, had reduced access to support staff and knowledge sharing opportunities in comparison to the day-time shift. To remedy this shortcoming, workers from different shifts self-organised around information distribution, heavily relying on self-organised collaboration and information distribution amongst operators. Lastly, efficient collaboration within the production cell with cobots does not only depend on the collaboration amongst robot operators but extends further into the organisation. Robot operators relied heavily on the availability of external support staff. These robot supporters, both from within the company as well as externally hired third-party collaborators, facilitated the robot introduction, but required a new type of collaboration spanning across multiple shifts and organisational structures.

This paper contributes with findings in relation to the impact that collaborative robots can have on the workplace. Specifically, how collaborative robots affect elements such as spatial setup, which can lead to unintended effects on interpersonal relationships both in- and outside of the production cell.

3.5 Paper V - Designing for Efficient Human-Robot Interaction

Paper V

Eike Schneiders, Stanley Celestin, Christopher Fourie, Guy Hoffman, Julie Shah, and Malte Jung. 2022. Understanding Entrainment in Human Groups: Identifying Cobot Design Considerations based on Human Collaboration.

As the previous studies have shown, collaboration with robots is less well defined and still has great potential for improvement. Human-human collaboration, however, often happens with ease during the completion of various tasks. Previous research has shown that human collaborators naturally entrain on each other, leading to a temporal synchronisation in actions. Examples of this include walking [129], dancing [122, 134], or general body movement [89, 121]. And while entrainment occurs naturally between human collaborators, it further brings with it a multitude of positive side effects including improved task performance [127], higher likeability amongst collaborators [56, 63], willingness to cooperate [91, 133], and rapport between collaborators [61, 62, 71].

In this paper, we used a mixed-method approach to identify how dyads (i.e., two human collaborators) and triads (i.e., three human collaborators) of humans entrain on each other during fast-paced, short-cycle repetitive tasks, as inspired by industrial pick-and-placing [94, 100]. To this end, we conducted a lab-study with 50 participants divided into ten dyads and ten triads. While groups were completing the pick-and-placing task, we utilised the OptiTrack system to track hand positions as well as key objects in the collaboration. Furthermore, two video cameras recorded audio-video material during task completion. Lastly, following the task, we conducted semi-structured group-based interviews, following an interview guide on pre-selected topics.

This paper contributed with a series of findings. Firstly, we show that the two conditions (i.e., dyadic and triadic collaboration) were performing evenly in relation number of task completions, thereby making them comparable. While existing literature argues for the natural occurrence of entrainment, we still had to verify that the task designed for this study indeed resulted in entrainment. To verify this, we used motion tracking data, analysis of which showed clear evidence for an increasing consistency—or temporal synchronisation—indicating entrainment. Secondly, we present two different strategies on how groups achieved temporal synchronisation. While some groups made a conscious decision to try to fall into a rhythm, other groups observed this happening without active effort. Thirdly, results highlighted three distinct types of leader-follower patterns, namely: static, flexible, and absence of a leader. While the dyads were characterised by the leader being the collaborator performing the 'bottleneck' task, triads had a greater variety in the applied strategy. Fourthly, clear differences in the amount and topic of interpersonal communication could be observed between dyads and triads. While dyads focused on task-unrelated small-talk, triads had a higher emphasis on task-related conversation. This might be an indication of the higher cognitive workload required in the triadic setting. Fifthly, groups utilised different strategies when deciding on the point-of-assembly, i.e., the physical location at which each collaborators sub-tasks meet. Nevertheless, the importance of consistent and predictable behaviour by all collaborators was mentioned as a key factor. Lastly, while auditory information—especially in the industrial context—is often considered noise, well placed audio cues are of importance as these free other senses, i.e., tactile and vision, for task completion.

Based on these findings, we propose three design consideration for the design of collaborative robots, ultimately aiming at improving non-dyadic human-robot collaboration. Firstly, we propose utilising sensory information to give robots the possibility to detect fluctuations in the human collaborators pace, thereby making adjustments to them possible. The motivation for this design consideration is based on the desire to reduce the extent to which humans adapt to the robot while increasing the extent at the robot adapts to the human collaborators, i.e., entrain, on one another. Secondly, the task chosen produced noise, while this was unintended, most participants perceived it as positive addition to the entrainment as it provided an additional task-intrinsic stimuli [123], thereby improving ease of entrainment. Based on these observations, we recommend the addition of robot produced auditory cues, strengthening the mutual entrainment by providing an additional stimuli. In addition to easing entrainment, this also allows for the sharing of information, without collaborators having to divide their visual attention between multiple collaborators sub-tasks. Lastly, we propose 'flexible consistency', meaning consistent behaviour throughout the course of the collaborative effort, while maintaining flexibility to adjust to individual collaborators naturally occuring fluctuations in performance.

This paper contributes with an investigation of human-centred non-dyadic collaboration. Based on this, we were able to identify a number of design considerations for the future research and design of collaborative robots, ultimately improving non-dyadic human-robot collaboration.

4 DISCUSSION

In this dissertation, I have investigated various aspects of collaboration during non-dyadic HRI, and how the addition of robots influences the interaction within and around collaborative efforts. This section will discuss some of the broader implications that arose from the presented papers.

In the studies completed as part of this dissertation, I have shown how non-dyadic interaction with robots is not just a collection of dyadic interactions, i.e., a multitude of one-to-one interactions. Contrasting dyadic HRI, non-dyadic interaction adds multiple additional complexities, challenges, and opportunities. These include e.g., Human-Human Interaction around single robots, for instance in the case of breakdown recovery and troubleshooting. This addition of Human-Human Interaction and collaboration within group based collaboration has the potential to change the entire interaction. This phenomena has been referred to as the 'ripple effect' [65], as described in Section 1.3. The following sections will highlight numerous aspects in which the introduction of robots during collaboration in non-dyadic settings influences the interaction. Specifically, this section will present three characteristics of collaborative non-dyadic Human-Robot Interaction related to i) task fragmentation during collaborative HRI (Section 4.1), ii) robots effect on interpersonal relationship during collaboration (Section 4.2), and iii) robots capabilities to shift roles and responsibilities. (Section 4.3). Lastly this section will present future work (Section 4.4) and limitations (Section 4.5).

4.1 Task Fragmentation in Collaborative Human-Robot Interaction

The first characteristic of non-dyadic Human-Robot Interaction during collaboration I want to highlight is the robot's influence on the task to be completed. The conducted studies show that the introduction of robots into various contexts and non-dyadic group configurations can result in the fragmentation of existing tasks. The term 'fragmentation' (introduced in Paper II & III) refers to the restructuring of existing coherent tasks into smaller sub-tasks, only some of which are automated through the robot's introduction. This observation was made both in the domestic as well as the industrial context.

As illustrated through the studies conducted as part of this dissertation, tasks change with the introduction of robots. In this dissertation, I considered a 'task' to be a sequence of actions required to achieve a specific goal. Consequently, each step in this sequence can be considered a sub-task that in one way or another contributes to achieving a specific goal. For instance, the goal of assembling a Lego set requires a series of sub-tasks such as i) finding the correct blocks for the current Lego module(s), ii) assembling the specific module(s), and iii) combining the completed modules into the final Lego set. The introduction of robots into tasks that impacts both the task and its completion along multiple parameters such as 'individual task involvement', 'steps needed to complete it', or 'timing of individual sub-tasks or steps'. This dissertation shows that this is the case in multiple contexts around vastly different tasks (e.g., lawn mowing or industrial assembly) and in a variety of contexts (i.e., private homes and the industrial context). For both contexts, clear differences could be observed in the way people organise around and complete tasks.

In both contexts investigated, tasks that participants considered one coherent task, i.e., vacuuming (described in Section 3.2) or welding (described in Section 3.3), have been fragmented into a series of sub-tasks only some of which are automated. These tasks can be categorised into three types of tasks, as illustrated in Figure 4.1, namely: the preparatory tasks, the primary task, and post-processing. The illustration is a simplified visualisation of one example on how sub-tasks could unravel. In reality this process can be more complex, i.e., preparatory tasks can be completed while temporally overlapping with the primary task. The preparatory tasks, as well as the post-processing, are categorised as peripheral tasks. The introduction of the robot highlights the, not always apparent, fact that the robot could only automate some of the aspects of the task requiring manual labour. Sub-tasks that required decision making, relied on tacit knowledge, or were unpredictable were not automated by the robots.

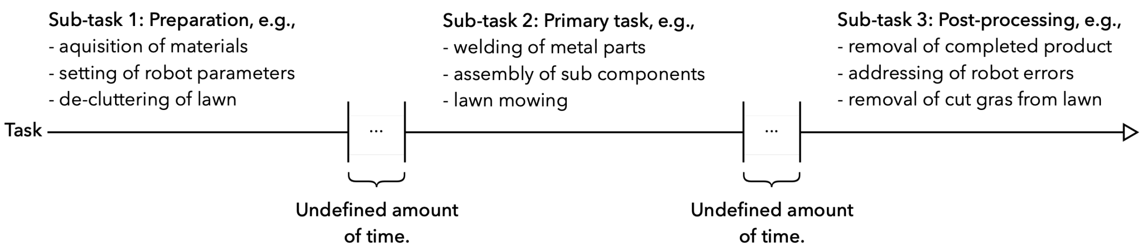


Figure 4.1: Timeline and fragmentation of tasks. One coherent task becomes divided into three sub-tasks, of which only one (i.e., the primary task) is automated through the robot. These individual sub-tasks (i.e., preparation, primary task, and post-processing) do not need to be temporally linked and can be disjointed with a flexible amount of time.

We observed task fragmentation in the domestic context, which is typically less structured than the industrial context. While the tasks were different, their fragmentation happened along the same lines as in industry: an established process, such as lawn mowing or floor mopping, was divided into a series of sub-tasks, one of which the robot automates. In the domestic context, these sub-tasks were temporarily and, at times, spatially divided. While prior to the robot introduction all tasks were completed in direct succession, this was not the case following the introduction of the robot. The preparation of the robot and the area in which it has to operate (e.g., de-cluttering or filling up the water tank) was done prior to the actual task, which was often started remotely. To exemplify this, I present two vignettes illustrating the difference between the activities and highlighting the individual sub-tasks necessary for the task of mowing. Vignette 1 presents Laura's situation prior to the robot lawn mower introduction.

Vignette 1. (Lawn mowing prior to the robot's introduction) *Following the decision to mow the lawn, Laura goes to the garden shed to find her electrical-powered lawn mower and the extension cord. After plugging the lawn mower in, she starts mowing the lawn in a systematic way from the garden shed towards the house. While mowing, she stops to throw her children's toys on the already mowed area of the lawn to clear the path whenever she encounters them. After completing the mowing activity, Laura pushes the lawn mower back into the shed, rolls the cable up, and hangs it on the designated spot next to the lawn mower. When necessary, Laura exchanges the blade of the lawn mower following the mowing.*

As can be seen in the above Vignette, the entire process of lawn mowing—including de-cluttering as well as maintaining—is one coherent process that is done in direct succession. This coherent process is fragmented into the three above-mentioned sub-tasks, two of which are considered peripheral tasks. This is described in Vignette 2 as presented below.

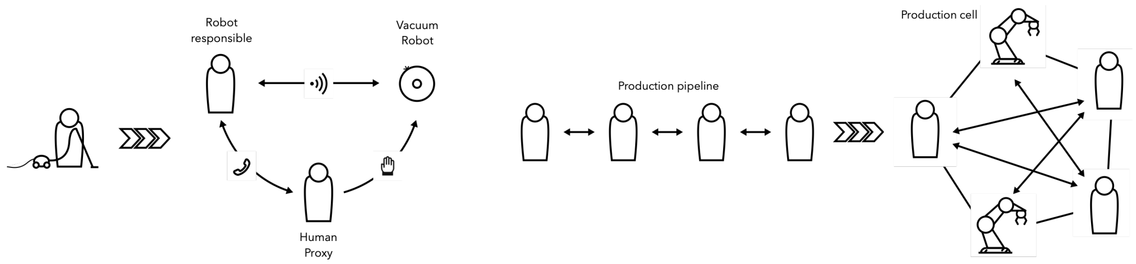
Vignette 2. (Lawn mowing following the robot's introduction) *(Sub-task 1) Following the decision to mow the lawn, Laura goes to the garden to remove her children's toys from the area to be mowed. After the lawn is de-cluttered and all toys etc. are put back in the toy box, Laura goes to her car to run some errands. After leaving home, she uses her phone to remotely start the lawn mowing robot. (Sub-task 2) While she is out the lawn mower robot mows the lawn. Upon returning home, the lawn mowing robot is back in its charger and the lawn has been mowed. (Sub-task 3) In the evening Laura's phone suggests to install a software update for the lawn mower.*

The coherent task of lawn mowing has been divided into three sub-tasks, only the primary tasks of which is being automated. While the fragmentation of tasks is not necessarily a problem, the findings presented highlight that this was not always the intend. Therefore, I argue for an increased consideration of how to address these side effects through a higher sense of transparency during automation.

4.2 Interpersonal Relationship and Collaboration

The second characteristic observed during collaborative non-dyadic Human-Robot Interaction is related to the interpersonal relationships between collaborators. The results presented throughout this dissertation illuminate how we collaborate with others and how our social relationships are influenced by the addition of robot collaborators. This was, to varying degrees, observed both in the domestic and in the industrial context.

As highlighted in Study II & IV, robots change how we relate to people in our surroundings when completing tasks. As exemplified in Section 4.1, the introduction of robots changes which tasks the human collaborator is responsible for, and which aspects are outsourced to the robot. The robot's addition changes the spatiality of the task at hand significantly. It allows the task, e.g., lawn mowing or vacuum cleaning, to be performed remotely, without the need for physical collocation. Furthermore, due to the previously described task fragmentation, it allows for specific sub-tasks to be completed prior to the primary task. This change allows for easier distribution and collaboration around sub-tasks. We observed, for instance, that robot owners in the domestic context at times resort to very low fidelity solutions in order to extend their robot's capabilities, namely the reliance on other technology and humans as proxies (see Figure 4.2a). Households would call or text other household members who were at home to initiate the operation of the robot(s). Furthermore, humans started to collaborate around the preparatory tasks (see Figure 4.1). This was typically implemented through a division of the household, in which each household member was responsible for the vacuum cleaners access to a specific subset of the household. This collaboration around the task led to a higher degree of involvement in the subsequent responsibility by all household members.



(a) Change of interpersonal interaction due to robot introduction in the domestic context.

(b) Spatial restructuring from production pipeline to production cell leading to an increase in interaction partners within the production cell.

Figure 4.2: The robots' effect on spatiality in the domestic and industrial context. Figure 4.2a highlights a simplified visualisation of how a robot can convert dyadic to non-dyadic interaction in the home. Figure 4.2b showcases how the introduction of the robot leads to restructuring, resulting in a positive change in interpersonal relationships, even though the robots caused a reduction of human employees in the cell.

In the industrial context, the addition of robots had wide-ranging effects on social interaction. The introduction changed how companies operate, starting with changes in the spatial setup of the production environment. This restructuring of the environment affected the proximity as well as quantity of human collaborators. Through this restructuring—which was necessitated to effectively use the new cobots—the number of social interactions increased (see Figure 4.2b). Surprisingly, this was observed even though the amount of human collaborators within the production cell decreased. The two vignettes 3 & 4 exemplify the effect of the cobot introduction on interpersonal relationships between collaborators facilitated by the spatial restructuring due to cobots.

Vignette 3. (Prior to cobot introduction) *Like every morning George enters the production floor and walks to the first position in the production pipeline where he will start today. The first station includes the inner press machine, used for pressing dents in the correct places into metal tubes, as well as inserting the metal threading into the pressed tube. Following these two steps, he places the tubes onto a wagon with a special holder for the tubes. Following the preparation of exactly 20 tubes, after the wagon is filled, he pushes the wagon over to station two for further processing. After one hour, each of the four positions rotates to the next position to maintain variety. Throughout the workday, he has limited conversation with the person(s) in the stations directly next to him.*

As highlighted in Vignette 3, prior to the cobot introduction the production floor consisted of several elongated production pipelines. These were characterised by the presence of four stations, each with a number of station-specific tasks. The physical distance between these stations limited the verbal communication amongst employees to interaction with the person(s) in adjacent stations. This was changed following the introduction of the cobots as illustrated in Vignette 4.

Vignette 4. (Following cobot introduction) *Like every morning George enters the production floor and walks to the first position in the production cell where he will start today. After Cobot 2 has filled the wagon with 20 metal cubes, George removes the wagon and brings it to the outer dent station—which currently is still manual—while Cobot 2 fills the next wagon. While pressing outer dents, George is in close proximity to Laura, who is currently addressing an issue with Cobot 1. While George presses the outer dents into the metal tubes, they talk about what could have caused the error and how to resolve it. George takes a short break from his task to assist Laura in resetting Cobot 1. Following this, he completes the outer denting of the remaining tubes and goes to Cobot 2 to take the next wagon with undented tubes. During the entire time, he is in close proximity with Laura, allowing them to converse about work-related topics, as well as private conversations.*

Vignette 4 illuminates several key differences between the before and after of the cobot introduction. Firstly, the entire structure of the production has switched from an elongated production pipeline into a production cell. This spatial change was necessitated due to the cobot's introduction, as this allowed to maximise the reachable area, thereby increasing the number of tasks that can be performed by the cobots. Furthermore, this change resulted in a reduction of workers compared to the pipeline layout. It could be expected that this change would therefore negatively affect social interactions. However, based on the conducted studies, we conclude that the potential for robots in the workplace to improve social interactions, as hypothesised by Smids et al. [109], holds true.

4.3 Shifting Roles and Responsibilities

The third characteristic of non-dyadic collaboration during Human-Robot Interaction is the robot's impact on collaborative roles and how it distributes and restructures existing roles and responsibilities. In the papers included in this dissertation, I have shown that the introduction of robots leads to the creation of new roles in both investigated contexts. While the interaction with the robot(s) at times relies on one primary responsible collaborator, introducing robots also creates, shifts, and removes responsibilities to previously uninvolved parties.

Changes in responsibilities amongst collaborators in non-dyadic settings when robots are introduced have been observed in contexts such as the health sector [72] and the domestic context [24, 35]. In this dissertation, and the included papers, I have further highlighted this change of responsibilities in two sectors. To mention two concrete examples, while one household member had the primary responsibility and interaction with the domestic robot(s), all household members were responsible for designated areas of the household/garden when it came to the 'preparation' phase (see Figure 4.1). Thereby, the robot challenged existing norms within the household [35], and involved household members who previously had no active role in the task of vacuuming/mowing. Furthermore, traditional roles in the household—i.e., women do the primary part of household chores such as cleaning [15]—were disrupted. Following the introduction of the domestic robots, all households investigated (involving more than one adult) presented that the male household member was predominantly responsible for the interaction and maintenance of the new technology. Reasons for this change could be the, in the households investigated, higher interest in 'gadgets' and new technology, incentivising the men in the household to take an interest in the task.

The effect on different roles and responsibilities was present to an ever greater extent in the industrial setting. Ironically, the introduction of collaborative robots was often presented to employees as a way to 'up-skill' employees, thereby allowing the robots to take over repetitive simple tasks and freeing the employees for more complex tasks. Nevertheless, we made, amongst others, contrasting observations. While robots indeed often took over repetitive tasks leading to higher consistency in output, the role of the worker changed drastically. The emphasis on robot automation in the industrial context led to a shift in task responsibility among the workers. This resulted in the feeling of losing one's job identity [141] as the tasks of e.g., welding or assembling, were now completed by the robot. The human workers' area of responsibility was shifted towards being a 'robot operator' or 'robot supporter,' focusing on peripheral tasks. Specifically, peripheral tasks handled by the operators included the preparation of material as well as observing in order to intervene during robot failures. This shift is illustrated by the two vignettes presented in Study IV, here in shortened form:

Vignette 5. (Industrial welder prior to cobot introduction) *Margot takes the two outer halves of a full circle and places them on a round, manually rotating table. Following this, the two inner halves of the circle are taken and placed inside the previous two rings, thereby forming a full circle profile with both inner and outer components.[...] She equips her welding helmet and starts welding the pieces together at regular distances. After each weld, she manually turns the rotatable table to bring the next point for welding into proximity. After the last weld is completed, she removes the now closed ring from the welding table and places it in the holding rack to start the process with the next round metal profile.* [21]

Vignette 5 describes the preparation, welding, and removal of the completed product. A coherent activity for which the responsibility is placed entirely on the welder. This changes entirely following the cobot introduction, as described in Vignette 6. Apart from the task being fragmented, as described in Section 4.1, the responsibility of the welder changes. While they were employed for welding, their responsibilities changed to peripheral tasks, including the new responsibility of material preparation and parameter tuning for the collaborative robot. Through this change in responsibility, the worker's job identity changes, from, i.e., 'welder'—a task requiring a high level of training—to 'cobot supporter'.

Vignette 6. (Robot supporter following the cobot introduction) *[Following the positions of the outer and inner halves] Margot retreats to the other side of the welding curtains, increasing the distance between the cobot [...]. Using the cobot control tablet, which is placed on the other side of the welding curtain roughly 3 meters from the cobot, she confirms that the parameters – such as waypoints or radius for welding head turns – are set up correctly. [...] Following each weld, the robot automatically re-poitions its welding end effector to the next welding position. During the next one to one and a half minutes [...], the cobot automatically places the pre-defined welds at a 20-30 cm distance. During this time, Margot waits on the other side of the welding curtain. Following the last weld, the robot retracts into the centre position of the table.* [21]

4.4 Future directions

While this dissertation answers a specific set of questions, it also raises new questions, opportunities, and future research directions. In this section, I will briefly highlight future research directions within non-dyadic HRI, thereby further contributing to a better understanding of groups based interaction and collaboration in non-dyadic Human-Robot Interaction.

4.4.1 Robots as Pro-active Collaborators

A common theme in the enclosed papers is the investigation of robots, of varying kinds and shape, as collaborators. Be it in the home or in industry, both contexts show a clear potential for utilitarian qualities of robots. Nonetheless, the advance of robots in numerous domains is not without flaws and shortcomings, and while modern robots can solve tasks of increasing complexity, they still lack context awareness and pro-active behaviour.

Robots still largely depend on human commands to perform given tasks. While I do not argue for removing humans from the collaborative equation, a higher degree of 'sense making' of the world from the robots' point of view could be beneficial for the robot. Pro-active behaviour during collaborative efforts could helps address some of the frictions that arise as a result of the task fragmentation discussed in Section 4.1. In the domestic context, robots capable of detecting when e.g., cleaning is needed, and, based on this, could inform the appropriate household member(s) to do the preparatory work. Similar effects could be achieved in non-dyadic HRI in the industrial context. Here, robots could adjust their pace to match the human workers, thereby better adjust to the specific workers and their daily performance, resulting in e.g., a prevention of fatigue. Furthermore, the increase in pro-active behaviour based on e.g., sensory information, could contribute to scenarios in which robots adapt to the user, and not vice versa (investigated in Paper V). In both cases, the increase of pro-active, or intelligent, behaviour can, in addition to resolving potential problems, result in new issues such as over-trust [5].

4.4.2 Transparency to Counter the Ironies of Automation

As Lisanne Bainbridge already postulates in 1982 [8], industrial automation, which aims to reduce workload and errors, also result in new problems. In this dissertation and the papers included in it, I have shown that this, 40 years later, still holds true. Furthermore, I have demonstrated how these ironies are not exclusive to industrial automation, but how the dream of automation also applies to other contexts, such as the private home. In order to alleviate these problems, one major step that needs to be taken is expectation alignment between robot developers and the robot users, as robots, as highlighted, are not a plug-and-play solution, neither in the home nor in industry.

As mentioned in Chapter 1, the investigation of interaction with robots, and especially robots as part of groups, is an area of research characterised by an emphasis on laboratory-based studies [60]. While lab-based studies can be tremendously useful, they lack the ecological validity of field studies. Furthermore, most lab studies are comprised of one-time interactions, making it difficult to investigate the effects of the robot's introduction beyond the novelty effect. The less controlled structure of real-world environments makes it difficult to anticipate the robots' effects—including side effects such as additional work introduced—on the interaction as well as the environment. Therefore, the investigation of interaction with robots also requires studies utilising the actual context of interaction, leading to a better understanding of the potential side-effects introduced by the robot introduction.

The three papers contained in this dissertation that investigate actual interaction with robots (i.e., Paper II - IV) focus this investigation on real-world contexts. Specifically, the two different real-world environments, namely the home as well as the industrial space, are chosen to investigate interaction and collaboration with and around robots in the wild. While the home is typically seen as a chaotic and unstructured environment, the industrial or manufacturing context is characterised by streamlined processes designed to ensure maximum efficiency and structure. Paper II, which investigated the domestic space, was characterised by the uniqueness of each household on a multitude of parameters, including types and number of robots, use of additional technologies, household members, and layout of the environment. Nevertheless, most households required adaptation on multiple dimensions including environment, digital ecology, as well as collaboration with other household members. With the industrial context being very different, we made surprisingly similar observations. The introduction of the robot(s)—or cobot(s)—not only fragmented existing routines as observed in the domestic context, but also necessitated spatial re-organisation of existing work setups. This effect has previously been observed in other domains such as robotic surgery [2, 85]. These necessary adjustments, both in the home as well as in the industrial space, are nearly impossible to predict as they arise as a side effect of robot introduction. Therefore, identifying unintended side-effects of robot introduction requires the investigation of non-dyadic HRI in unstructured, real-world environments outside the lab.

4.4.3 What is Collaboration?

I have started this dissertation by presenting an existing understanding of collaboration (see Section 1.3). Furthermore, I have presented the formal definition of a collaborative robot, which is intended for collaboration between humans and robots. Following the research endeavours presented in this dissertation, the question arises: what characterises a collaborative robot? Is the definition by Peshkin and Colgate [25] still applicable or useful? As this definition is 25 years old, it might require reconsideration and reexamination in order to evaluate its current applicability. In this dissertation, the term 'collaboration'—relevant both between people as well as between robots and people—is of central importance. With this being the case, the use of the term 'collaboration' and collaborative robot (cobot) is not the one patented in 1997 by Peshkin and Colgate, but takes a wider stance allowing for a broader understanding of what collaboration means and what can be considered a collaborative robot. The criterion I apply for delimiting a specific robot as a robot for collaboration is based on the purpose of the Human-Robot Interaction and not on its hardware or capabilities, as the original definition required a 'general purpose manipulator'. Following this line of thought, any robot that works together with other actors in order to complete a given task to achieve a shared goal is considered a collaborative robot. Future research could investigate a new formalisation of what collaboration with robots means.

4.5 Limitations

This dissertation has some limitations in relation to the applied understanding of the term 'robot', the focus on qualitative methods, the potential lack of generalisability, and the lack of variety in geographical locations of the field studies.

As presented in Chapter 2, a multitude of different definitions of the term robot exists, and while I only have presented a selected few, many more are available. To limit the scope of this dissertation and the papers included, I chose an understanding highlighting the necessity for 'physical embodiment', thereby delimiting my research from, e.g., software robots. The understanding chosen (see Chapter 1), was furthermore inspired by the 'Sense-Plan-Act' paradigm [23]. The application of a different understanding of the term robot, might highlight different results.

Throughout this dissertation, I have primarily utilised qualitative methods to investigate non-dyadic Human-Robot Interaction and collaboration. Examples include interviews, technology staging, or on-site observations. While these methods can provide in depth information about the influence of robots in the investigated contexts, quantitative methods could provide different, potentially with higher generalisability, results.

The last four papers (Paper II-V) are based on two specific contexts in which non-dyadic Human-Robot Interaction was observed. The described findings are based on these two specific contexts, therefore I can not know how generalisable these are outside of the domestic and industrial context. Furthermore, all three field studies (Paper II - IV) have been conducted in Denmark. To identify if the findings presented in this dissertation are applicable outside the here studied contexts or geographic location is left for future studies.

4. DISCUSSION

5 CONCLUSION

At the beginning of this dissertation, I argued for the need to emphasise research on non-dyadic Human-Robot Interaction, as robots in non-dyadic configurations are becoming more common and can be encountered in a growing number of domains. Throughout the course of this dissertation, and the five contained papers, I have investigated two specific research questions.

The first research question is directed at a retrospective classification of existing research on Human-Robot Interaction.

RQ1: *What characterises non-dyadic Human-Robot Interaction research?*

To investigate RQ1, we conducted a literature review based on 164 HRI Conference publications (2006 – 2020) investigating non-dyadic Human-Robot Interaction. We adapted an existing multi-human and multi-artefact HCI framework [110] to classify non-dyadic HRI research. Inspired by Sørensen et al. [110] and Yanco and Drury [136], we considered different configurations between human(s) and embodied devices, including robots. We divided the article corpus into three specific configurations (human-to-device) for a systematic classification: one-to-many, many-to-one, and many-to-many.

The literature review helped to crystallise two specific characteristics for non-dyadic Human-Robot Interaction research. Firstly, while the amount of non-dyadic research is growing—from less than 10% to nearly 40% over a decade, a clear focus on the one-to-many configurations becomes apparent. Thereby we were able to present empirical evidence for an ongoing paradigm shift [77]. Specifically, 52% of HRI Conference publications emphasise Human-Robot Interactions in which multiple robots (and other devices) but only one human participant is present. Secondly, when looking at the temporal dimension, a distinction can be made between simultaneous and sequential interaction with robots in groups. Here, we identified an overwhelming tendency of HRI research to emphasise the simultaneous usage of multiple devices (85%).

The second research question focuses on the investigation of the robots influence on collaboration during non-dyadic Human-Robot Interaction.

RQ2: *What influence do robots have on collaboration in non-dyadic Human-Robot Interaction?*

To answer this research question, we conducted four empirical studies focusing on the two contexts of the home and industry. These studies contribute with a new understanding of how robots influence collaboration in multiple contexts and along multiple dimensions. To answer RQ2, I highlight three specific influences of robots on collaboration during non-dyadic Human-Robot Interaction.

Firstly, we showed that the addition of robots into non-dyadic configurations influences the task around which the actors collaborate. Specifically, a task that—pre-robot introduction—was perceived to be coherent was fragmented into three individual phases: preparatory, primary, and post-processing. However, the robot(s) introduction, contrasting to user expectation, was only able to automate the primary task. Secondly, the introduction of robots did not only affect how the task at hand was completed but also influenced collaborators' interpersonal relationships. This was possibly due to two primary changes, namely the robot's effect on who was involved in the task, as well as the robot's effect on the spatial layout of the environment. We were able to confirm the hypothesis by Smids et al. [109], illustrating that the introduction of robots is not just a threat but can result in a positive impact in relation to the quality and quantity of social interactions and the feeling of closeness amongst collaborators. Thirdly, the robot introduction adds, removes, and re-configures roles and responsibilities within the collaborative configuration. Tasks that previously were considered defining tasks for the specific role held by the human collaborator were removed, leading to loss of job identity. Contrastingly, the addition of robots into the existing environment can transform previously dyadic tasks into non-dyadic tasks and delegate responsibilities to previously uninvolved collaborators.

In this dissertation, I have argued for the need to emphasise research on various aspects of non-dyadic Human-Robot Interaction and collaboration due to the increase of real-world domains in which non-dyadic interaction with robots can occur. Based on this, I have investigated two research questions. To answer research question 1, I have presented a retrospective look at Human-Robot Interaction research, synthesising past and ongoing trends in non-dyadic HRI research. Following this, to answer research question 2, I have conducted four empirical studies to highlight the various ways in which the addition of robots into collaborative non-dyadic Human-Robot Interaction affects collaboration. Lastly, I have presented future research directions to explore promising opportunities within the field of non-dyadic Human-Robot Interaction.

5. CONCLUSION

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APPENDIX

This appendix contains the following five papers constituting the primary contribution of this dissertation.

1. **Eike Schneiders**, EunJeong Cheon, Jesper Kjeldskov, Matthias Rehm, and Mikael B. Skov. 2022. Non-Dyadic Interaction: A Literature Review of 15 Years of Human-Robot Interaction Conference Publications. *ACM Transactions of Human-Robot Interaction (THRI)*. 11, 2, Article 13 (June 2022), 32 pages. https://doi.org/10.1145/3488242

2. **Eike Schneiders**, Anne Marie Kanstrup, Jesper Kjeldskov, and Mikael B. Skov. 2021. Domestic Robots and the Dream of Automation: Understanding Human Interaction and Intervention. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 241, 1–13. https://doi.org/10.1145/3411764.3445629

3. EunJeong Cheon, **Eike Schneiders**, and Mikael B. Skov. 2022. Working with Bounded Collaboration: A Qualitative Study on how Collaboration is Co-constructed around Collaborative Robots in Industry. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

4. EunJeong Cheon, **Eike Schneiders**, Kristina Diekjobst and Mikael B. Skov. 2022. Robots as a Place for Socializing: Influences of Collaborative Robots on Social Dynamics In- and Outside the Production Cell. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

5. **Eike Schneiders**, Stanley Celestin, Christopher Fourie, Guy Hoffman, Julie Shah, and Malte Jung. 2022. Understanding Entrainment in Human Groups: Identifying Cobot Design Considerations based on Human Collaboration.

Each paper will be preceded by a page presenting the title, abstract, and publication information, followed by the paper. The digitally available version of this dissertation is redacted and contains only each paper's title, abstract, and publication information.

Paper I

Non-Dyadic Interaction: A Literature Review of 15 Years of Human-Robot Interaction Conference Publications

Abstract

Going beyond dyadic (one-to-one) interaction has been increasingly explored in HRI. Yet we lack a comprehensive view on non-dyadic interaction research in HRI. To map out 15 years of works investigating non-dyadic interaction, and thereby identifying the trend of the field and future research areas, we performed a literature review containing all 164 publications (2006-2020) from the HRI conference investigating non-dyadic interaction. Our approach is inspired by the 4C framework, an interaction framework focusing on understanding and categorising different types of interaction between humans and digital artefacts. The 4C framework consists of eight interaction principles for multi-user/multi-artefact interaction categorised into four broader themes. We modified the 4C framework to increase applicability and relevance in the context of non-dyadic human-robot interaction. We identify an increasing tendency towards non-dyadic research (36% in 2020), as well as a focus on simultaneous studies (85% from 2006-2020) over sequential. We also articulate seven interaction principles utilised in non-dyadic HRI and provide specific examples. Lastly, based on our findings, we discuss several salient points of non-dyadic HRI, the applicability of the modified 4C framework to HRI and potential future topics of interest as well as open-questions for non-dyadic research.

Eike Schneiders, EunJeong Cheon, Jesper Kjeldskov, Matthias Rehm, and Mikael B. Skov. 2022. Non-Dyadic Interaction: A Literature Review of 15 Years of Human-Robot Interaction Conference Publications. *ACM Transactions of Human-Robot Interaction (THRI)*. 11, 2, Article 13 (June 2022), 32 pages. https://doi.org/10.1145/3488242

Paper II

Domestic Robots and the Dream of Automation: Understanding Human Interaction and Intervention

Abstract

Domestic robots such as vacuum cleaners or lawnmowers are becoming popular consumer products in private homes, but while current HCI research on domestic robots has highlighted for example personalisation, long-term effects, or design guidelines, little attention has been paid to automation. To address this, we conducted a qualitative study with 24 participants in private households using interviews, contextual technology tours, and robot deployment. Through thematic analysis we identified three themes related to 1) work routines and automation, 2) domestic robot automation and the physical environment, as well as 3) interaction and breakdown intervention. We present an empirical understanding of how task automation using domestic robots can be implemented in the home. Lastly, we discuss our findings in relation to existing literature and highlight three opportunities for improved task automation using domestic robots for future research.

Eike Schneiders, Anne Marie Kanstrup, Jesper Kjeldskov, and Mikael B. Skov. 2021. Domestic Robots and the Dream of Automation: Understanding Human Interaction and Intervention. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 241, 1–13. https://doi.org/10.1145/3411764.3445629

Paper III

Working with Bounded Collaboration: A Qualitative Study on How Collaboration is Co-Constructed around Collaborative Robots in Industry

Abstract

We investigate how collaboration is understood and configured in industrial workplaces with collaborative robots (cobots). Through a qualitative analysis of 115 case studies of companies using cobots and 14 semi-structured interviews with cobot manufacturers and users, we examine the usages of cobots in the manufacturing industry over the entire temporal spectrum from pre-introduction to completed implementation. By synthesizing diverse stakeholders' perspectives, we present a set of main findings; key roles of a few supportive production workers during the adoption of cobots; a fragmentation of work tasks and the resulting loss of job identity among workers; the disunified meaning of "collaboration" which is under constant development; and the collaborative space and the working rhythms between production workers and cobots. By reconsidering what collaboration means in the workplace with cobots, we propose the concept of bounded collaboration, which means that the anticipated collaboration is manifested in a partial and limited manner within a collaborative technology. Finally, we provide practical suggestions for examining and supporting organizations and users in their adoption of cobots.

EunJeong Cheon, **Eike Schneiders**, and Mikael B. Skov. 2022. Working with Bounded Collaboration: A Qualitative Study on how Collaboration is Co-constructed around Collaborative Robots in Industry. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

Paper IV

Robots as a Place for Socializing: Influences of Collaborative Robots on Social Dynamics In- and Outside the Production Cell

Abstract

Introducing robots in the workplace entails new practices and configurations at the individual, organizational, and social levels. Prior work has focused on how robots may have an immediate effect on individual employees or tasks rather than their gradual influences on employees collectively or their organization over time. By drawing on fourteen in-situ interviews with six cobot operators in a Danish manufacturing company, this paper investigates how collaborative robots (cobots) in the manufacturing context may engage broader interactions beyond the robot-operator interaction. This includes spatial configurations centering around the cobots, social interactions among employees, and information flow through, within, or outside the production cell. Introducing and implementing cobots has social dynamics at its core, which we explore in-depth. This paper argues that the design of cobots and the environment around them should accommodate the possibility of more complicated social and organizational changes brought about by these robots. Lastly, we discuss research and design implications for the future of workplaces involving robots.

EunJeong Cheon, **Eike Schneiders**, Kristina Diekjobst and Mikael B. Skov. 2022. Robots as a Place for Socializing: Influences of Collaborative Robots on Social Dynamics In- and Outside the Production Cell. To appear in *Proceedings of the ACM on Human-Computer Interaction (CSCW). In Press*

Paper V

Understanding Entrainment in Human Groups: Identifying Cobot Design Guidelines based on Human Collaboration

Abstract

Temporal synchronisation amongst collaborators positively effects trust, willingness to collaborate, and likeability towards collaborators. This paper presents a mixed-method lab study to investigate characteristics of group based temporal synchronisation as a result of successful entrainment. Inspired by industrial work, we develop and prototyped a fast-paced, short-cycle repetitive task. Using motion tracking, we identify the occurrence of entrainment in both the dyadic and triadic completion of the selected task. We utilise audio-video recordings and semi-structured interviews to contextualise participants' experiences. This paper contributes to the HRI literature by using a human-centred approach to identify pair- and group-based entrainment characteristics during collaborative tasks. Firstly, we identified two different strategies for temporal synchronisation: conscious and coincidental entrainment. Secondly, we identify three different leader-follower patterns: static, flexible, and absent. Thirdly, we highlight differences in interpersonal communication between dyads and triads, pointing towards a potential difference in cognitive workload during task completion in these two different configurations. Lastly, we argue for the importance of sensory information, such as acoustic cues, to strengthen the mutual entrainment by providing task-intrinsic stimuli. Based on the presented findings, we highlight design considerations for future research on human-robot entrainment in non-dyadic collaboration.

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